Mohamed Behnassi
Himangana Gupta
Mirza Barjees Baig
Ijaz Rasool Noorka *Editors*

The Food Security, Biodiversity, and Climate Nexus

Springer

The Food Security, Biodiversity, and Climate Nexus

Mohamed Behnassi · Himangana Gupta ·
Mirza Barjees Baig · Ijaz Rasool Noorka
Editors

The Food Security, Biodiversity, and Climate Nexus

Springer

Editors
Mohamed Behnassi
Economic, Social and Environmental Council (ESEC)
Rabat, Morocco

Research Center on Environment, Human Security and Governance (CERES)
Rabat, Morocco

Mirza Barjees Baig
Prince Sultan Institute for Environmental, Water and Desert Research
King Saud University
Riyadh, Saudi Arabia

Himangana Gupta
Manager
Sustainable Landscapes and Restoration Program
World Resources Institute
New Delhi, India

Ijaz Rasool Noorka
Department of Plant Breeding and Genetics, College of Agriculture
University of Sargodha
Sargodha, Pakistan

ISBN 978-3-031-12585-0 ISBN 978-3-031-12586-7 (eBook)
https://doi.org/10.1007/978-3-031-12586-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword by Prof. Kazuhiko Takeuchi

Over recent decades, technological innovation has improved food production efficiency so much that the net loss of land has been reduced to zero worldwide, even as the global population continues to grow. However, some of the most biodiverse parts of the world—mostly in the tropics—are still being converted to agriculture. The global population is not expected to peak until around the end of the twenty-first century, and consumption patterns continue to rise, so agricultural efficiency will have to continue improving to meet growing demand and avoid even more ecological transformation. Meanwhile, in many temperate parts of the world, the abandonment of agricultural land can also result in the net loss of biodiversity.

Most of the media's attention to environmental issues is devoted to the threat of climate change. But terrestrial and marine biodiversity loss, mostly through the conversion of tropical ecosystems to large-scale agriculture, and the wild-catching of ocean fish, is already compromising the well-being of millions. And, this issue is not divorced from the climate. Climate change can exacerbate biodiversity loss, while functioning ecosystems can help mitigate and adapt to climate change.

Global attention to the links between food, climate, and biodiversity dates back decades. Coverage has increased recently, with publications like the OECD's "Towards Sustainable Land Use: Aligning Biodiversity, Climate and Food Policies," and a report jointly produced by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC). Renewed attention has been directed at nature-based solutions such as socio-ecological production landscapes and seascapes (SEPLS), which are characterized by production but managed in such a way that biodiversity can thrive. Well-managed SEPLS can also contribute to climate change mitigation and help build resilience to its effects.

This book attempts to illustrate the nexus between food, biodiversity, and climate and to highlight both the synergies and the trade-offs involved in decision-making around these issues. Featuring conceptual and empirical research covering 24 case studies from around the world, it addresses the impacts of climate change on biodiversity, ecosystem services, and food security, as well as its broader implications. It explores scientific and traditional solutions and biodiversity-friendly technologies to tackle climate change. It is well timed to coincide with the IPBES assessment on the interlinkages between biodiversity, water, food, and health. I trust that it proves to be a useful resource to the assessment authors and to researchers in integrated sustainability science more generally.

Tokyo, Japan

Prof. Kazuhiko Takeuchi
President, Institute for Global Environmental Strategies (IGES)
Project Professor, Institute for Future Initiatives, The University of Tokyo
Visiting Professor, United Nations University, Institute for the Advanced Study of Sustainability (UNU-IAS)
Acting Chair, Central Environment Council, Government of Japan
Chair, Nature Conservation Committee of the Central Environment Council, Government of Japan
Editor-in-Chief, Sustainability Science (Springer Nature)
Distinguished Chair, Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi
k-takeuchi@iges.or.jp

Foreword by Fred Kruidbos

Ecology is the study of the relationships between organisms and their natural environment. An easily understandable way in which these relationships can be interpreted is that between plant, herbivore, and predator. Because the conditions on Earth vary by region, the form, function, and relationships of species are expressed in different biomes, such as those of tropical forest, savanna, and desert, and the forests and grasslands of the temperate regions which all include humans. One of the most important ways in which humans influence their natural environment is their enormous technological capacity to provide for their basic needs. This has contributed greatly to the growth of the human population to about eight billion people today, but has also led to the disappearance of original habitats, biodiversity loss, and the unsustainability of social–ecological systems.

As in any ecosystem, humans are also distributed in some way within the boundaries of their habitat, preferably close to water. This distribution is therefore not homogeneous by nature and so present-day humans mainly live aggregated in urban areas and where farming and fishing can be practiced. What is striking here is that there are areas where few people live but a lot of food is produced and areas where this is the other way around. This implies an inequality in the availability of food. Due to international trade and logistics, food can in principle be distributed all over the world; but in practice, however, this is not the case. Food shortage often leads to extremes ranging from malnutrition and starvation to severe obesity and all the secondary consequences that result. One of the main causes of these inequalities lies not only in the nature of the habitat in which the affected human populations reside, but in the man-made economic system that prevails. An important indicator is financial inequality.

Financial inequality can be related, among other things, to capitalism from which deep traces have been left in so many households, including in the areas of food security, biodiversity, and climate change. Or, as economist James Galbraith puts it in his book *The Predator State*, public institutions have been undermined to serve private profits for business elites acting as "predators" whose interests run the state "not for any ideological project—but simply in a way that would bring to them, individually and as a group, the most money." A simple example in which these relationships are expressed is the large parts of tropical forests that have been cleared to provide for the production of soy, palm oil, wood, and meat. This often leaves the local population underpaid with a completely vulnerable social–ecological context while a few take the loot. Other examples of unsustainable business can be found in the production of cut flowers and Harico verts that are flown from East Africa to Western Europe or in cattle that grow up in arid landscapes of East Africa as a competitor to wild animals, contributing to desertification, before being shipped to Saudi Arabia for consumption. Precisely because of the scale and duration at which these practices take place, it has even had an impact on the global climate and therefore on all of us. So, the behavior of some has an influence on all.

Through a more holistic view and integration of current knowledge in the areas of food technology, land use, food safety, and equality, it is possible to contribute in a sustainable way to the food needs of every citizen worldwide. A major advantage of equal distribution of resources, and thus reducing inequalities, is that this will contribute enormously to human well-being and security. This is not only important from a humanitarian point of view, but it also contributes to slowing down global population growth. After all, it is known that an increase in prosperity leads to a decrease in reproduction, one of the important factors that contributes to the mitigation of the current resource scarcity challenge. A very important factor therefore remains the fundamental inequality between the Global North and the Global South. That is why the United Nations has formulated the following three sustainable development goals first: no poverty, no hunger, and good health and well-being.

It is my belief that the intentions of the editors of this volume to contribute in a multidisciplinary manner to a better understanding of the interrelationships between food security, biodiversity, and climate will certainly influence the achievement of the UN-appointed sustainable development goals. Precisely, by (re)exposing a number of fundamentally important aspects from a biological basis, such as the importance of biodiversity as the source of current and future ecosystem services, emphasizing the sensitivity of ecosystems to climate change, and the associated food security, it fuels the resistance against inequality. It is my fervent hope that this volume, which is complementary to the previous volumes published by CERES—Social-Ecological Systems: From Risks and Security to Viability and Resilience and The Climate Change-Conflict-Displacement Nexus—will contribute to the realization of a paradigm shift for the benefit of humanity and nature.

Helmond, Netherlands Fred Kruidbos

Fred Kruidbos is Biologist specialized in animal ecology. He studied at the prestigious Wageningen University and Fontys University of Applied Science, Tilburg. He is an independent researcher and the director of K-SN Ecological Services B.V. based in the Netherlands. His company operates worldwide and consists of three branches focused on: ecological research and consultancy; ecological products; and ecological safety and security services. This setup makes it possible to study problems from a multidimensional approach facilitating more holistic solutions. His current research is pragmatic in nature and focuses mainly on the interface between spatial planning and nature conservation. In addition to his civil studies, he completed the training as reserve officer and senior officer at the Netherlands Defense Academy (NLDA) and is attached to the Ministry of Defense as a Senior Operational Advisor. Supported by the combination of his ecological and military knowledge, he highlights issues from a different angle than is usual within both disciplines.

Acknowledgements

The idea of publishing this contributed volume, as a part of a series of CERES publications, stemmed from my contribution as a nominated expert in the Scoping assessment of the interlinkages among biodiversity, water, food, and health in the context of climate change undertaken by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on 2020. At the moment of writing these words, two co-editors of this book, Dr. Himangana Gupta and I, have been selected by the IPBES as lead author and review editor, respectively, to take part in the Nexus assessment of the interlinkages among biodiversity, water, food, and health, to be released on 2024.

This volume is the outcome of an international cooperation between 73 authors—scientists, experts, and practitioners—from many countries, disciplines, and professional areas. It aims at providing a comprehensive understanding of the linkages between food security, biodiversity, and climate change, especially in the context of Global South. Based on a multi-regional and cross-sectoral analysis, the approach consists of: assessing the different natural and anthropogenic factors currently affecting ecosystems and their services, especially the impacts of environmental and climatic changes; highlighting the different linkages between the state of biodiversity and food systems in many contexts and scales; and exploring and assessing the effectiveness of various response mechanisms to effectively manage the implications of such linkages.

I have been honored to share the editorship of this volume with my colleagues: Dr. Himangana Gupta (Manager, Sustainable Landscapes and Restoration Program, World Resources Institute (WRI), India); Dr. Mirza Barjees Baig (Researcher, Prince Sultan Institute for Environmental, Water, and Desert Research, King Saud University, Saudi Arabia); and Ijaz Rasool Noorka (Professor, Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Pakistan). I seize this opportunity to thank all of them for their precious collaboration during the publishing process.

The real value of this volume should be, however, credited to chapters' authors, whose works had been accepted for publication after a rigorous peer review and proofreading. Their collaboration, reactivity, and engagement during the process were indeed very remarkable and impressive. Therefore, any shortcomings are undoubtedly the editors' responsibility.

The chapters published in this volume are also the result of the invaluable contribution made by reviewers, who generously shared their time and energy to provide insight and expertise regarding the volume's chapters. On behalf of my co-editors, I would specifically like to acknowledge, with sincere and deepest thanks, the following reviewers:

- Dr. Rodolfo Dirzo, Department of Biology, Stanford University, USA
- Dr. Rurik List, Universidad Autónoma Metropolitana, Mexico
- Dr. José Luis Riveros, Pontificia Universidad Católica de Chile, Santiago, Chile
- Dr. Salih Gucel, Yakın Doğu, Environmental Research Center Üniversitesi, Near East University, Turkey
- Dr. Mohamed Zakaria Hussin, Department of Forest Science and Biodiversity, Serdang, Selangor, Malaysia
- Dr. Ibrahim Ozdemir, Department of Wildlife Ecology and Management, Isparta University of Applied Sciences, Cunur Isparta, Turkey
- Dr. Muhammad Zafar, Department of Plant Sciences, Quaid-i-Azam University, Islamabad, Pakistan
- Dr. Arshad Mahmood Khan, Department of Botany, Government Hashmat Ali Islamia Degree College Rawalpindi, Pakistan
- Patrick Lhomme, Research Institute for Biosciences, University of Mons, Belgium
- Dr. Moulay Chrif Smaili, National Institute for Agricultural Research (INRA) and CRRA-Kénitra, Morocco
- Dr. Humera Nazneen, Department of Botany, Nizam College, Osmania University, Hyderabad, Telangana, India
- Dr. Faiza Shaikh, Plant Ecologist/Environmentalist, Milton, Ontario, Canada
- Dr. Brent L. Nielsen, Department of Microbiology and Molecular Biology, Brigham Young University, Provo, Utah, USA
- Shahina A. Ghazanfar, Research Associate, Royal Botanic Gardens, Kew, UK
- Dr. Mir Ajab Khan, Quaid-e-Azam University, Islamabad, Pakistan
- Dr. Muhammad Arshad, Department of Botany, PMAS Arid Agriculture University, Rawalpindi, Pakistan
- Dr. Muhammad Siddiq, Food Sciences, Michigan State University, USA
- Dr. Karim-Aly S. Kassam, College of Agriculture and Life Sciences, Cornell University, Ithaca, New York, USA
- Dr. Murodbek Laldjebaev, School of Arts and Sciences, University of Central Asia, Tajikistan, Kyrgyz Republic, Kazakhstan
- Dr. Shafaqat Ali, Department of Environmental Sciences and Engineering, Government College University, Faisalabad, Pakistan
- Dr. Paul Dijkwel, School of Fundamental Sciences, Massey University, Palmerston North, New Zealand
- Dr. Arshad Mahmood, Soil Scientist, Brunei Agricultural Research Center, Brunei Darussalam

- Dr. Muhammad Aamer Maqsood, Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan
- Dr. Paul Dijkwel, School of Fundamental Sciences, Massey University, Palmerston North, New Zealand
- Dr. Hassan M. El Shaer, President of the Egyptian Center of Excellence for Biosaline Agriculture, Desert Research Center (DRC), Cairo, Egypt
- Dr. Rabia Afza, Department of Botany, Hazara University, Mansehra, Khyber Pakhtunkhwa, Pakistan
- Dr. Muhammad Nawaz Rajpar, Department of Forestry, Faculty of Life Sciences, Shaheed Benazir Bhutto University, Sheringal, Dir (Upper), Khyber Pakhtunkhwa, Pakistan
- Dr. Yinglong Chen, The UWA Institute of Agriculture, and School of Agriculture and Environment, the University of Western Australia, Perth, Australia
- Dr. Md. Nur Alam, Department of Pharmacy, Jahangirnagar University, Savar, Dhaka, Bangladesh
- Dr. Fazleen Abdul Fatah, Faculty of Plantation and Agrotechnology, Universiti Teknologi MARA, Jasin Campus, Melaka, Malaysia.

Mohamed Behnassi

About the Publishing Institutions

The Center for Environment, Human Security and Governance (CERES), Morocco

CERES, previously the North-South Center for Social Sciences (NRCS), 2008–2015, is an independent and not-for-profit research institute founded by a group of Moroccan researchers and experts in 2015 and joined by many partners worldwide. It aspires to play the role of a leading think tank in the Global South and to serve as a reference point for relevant change processes. Since its creation, CERES managed to build a robust network involving various stakeholders such as researchers, experts, Ph.D. students, decision-makers, practitioners, and journalists from different spheres and scientific areas. These achievements are being rewarded by the invitation of CERES members to contribute to global and regional assessments and studies (especially IPBES, MedECC, EuroMeSCo, etc.) and the invitation of the Center to become a member of the MedThink 5+5, which aims at shaping relevant research and decision agendas in the Mediterranean Basin. The Center has organized so far five international conferences and several training/building capacity workshops, provided expertise for many institutions, and published numerous books, scientific papers, and studies which are globally distributed and recognized. These events and publications cover many emerging research areas mainly related to the human–environment nexus from a multidimensional, multiscale, interdisciplinary, and policy-making perspectives. Through its initiatives, the CERES attempts to provide expertise, to advance science and its applications, and to contribute to effective science and policy interactions.

The Prince Sultan Institute for Environmental, Water and Desert Research (PSIEWDR), King Saud University, Riyadh, Kingdom of Saudi Arabia

PSIEWDR was established in 1986 to conduct scientific research related to environmental issues and water resources. It also engages with vital issues related to the problem of aridity and the desert environment. It conducts development initiatives for the country's desert areas, particularly programs for combating desertification in the Arabian Peninsula. PSIEWDR designed and carried out two major water harvesting and storage programs, including the construction of purpose-built infrastructure, throughout the Kingdom of Saudi Arabia using novel techniques and equipment. The institute actively applies remote sensing technologies using advanced satellite image processing systems and GIS to study the country's environment and natural resources. In 2007, the institute published *The Space Image Atlas of the Kingdom of Saudi Arabia*, and it is currently developing *The Environmental Atlas of the Kingdom of Saudi Arabia.* The institute has been the primary sponsor of the biennial International Conference on Water Resources and Arid Environments (ICWRAE) held in Riyadh, Saudi Arabia, since 2004. The institute hosts the General Secretariat of the Prince Sultan Bin Abdulaziz International Prize for Water (PSIPW) which honors scientists all over the world for their innovative water-related research. PSIPW, in turn, has many agreements with various international water associations as well as a close partnership with the United Nations. PSIPW and the United Nations Office of Outer Space Affairs (UNOOSA) jointly produce and maintain the International Space4Water Portal, an online hub for all stakeholders involved in utilizing space technologies for water resources applications.

Contents

Editors and Contributors

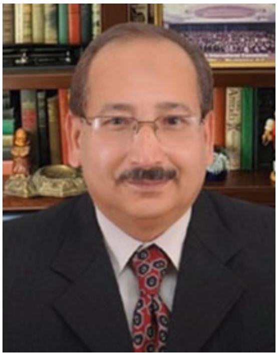
About the Editors

Dr. Mohamed Behnassi is currently a Senior Environmentalist Expert at the Economic, Social and Environmental Council (ESEC), Rabat, Morocco. From Dec. 2004 to June 2022, he was Professor at the College of Law, Economics, and Social Sciences, Ibn Zohr University of Agadir. He holds a PhD in International Environmental Law and Governance (Hassan II University of Casablanca, 2003) and a Diploma in International Environmental Law and Diplomacy (University of Eastern Finland and UNEP, 2015). He is currently the Founding Director of the Center for Environment, Human Security and Governance (CERES)—Former North-South Center for Social Sciences (NRCS). From 2015 to 2018, he was the Director of the Research Laboratory for Territorial Governance, Human Security and Sustainability (LAGOS).In recent years, he was appointed as Expert Evaluator by the National Center for Scientific and Technical Research (CNRST/Morocco), Scoping Expert and Review Editor by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and Lead Author and Coordinating Lead Author by the Mediterranean Experts on Climate and Environmental Change (MEDECC). Dr. Behnassi's main research and expertise area includes international law and politics of environment and human security. In these areas, he published considerable number of scientific papers and book chapters in addition to 20 books, including recent ones on: Food Security and Climate-Climate Smart Food Systems—Building Resilience for the Global South (Springer, 2022); The Climate-Conflict-Migration Nexus from a Human Security Perspective (Springer, 2022); and Social-Ecological Systems in the Era of Risks and Insecurity—Pathways to Viability and Resilience (Springer, 2021). Dr. Behnassi serves as a reviewer for many global publishers (such as Routledge and Springer) and scientific journals with high impact factor. He has organized many international conferences covering the above research areas, managed many research and expertise projects, and is regularly requested to provide scientific expertise nationally and internationally. Other professional activities include social compliance auditing and consultancy by monitoring human rights at work and the sustainability of the global supply chain.

Dr. Himangana Gupta is Manager, Sustainable Landscapes and Restoration Program with the World Resources Institute in New Delhi, India. She is also Visiting Research Fellow at United Nations University Institute for the Advanced Study of Sustainability (UNU-IAS), Tokyo.

Before this, she was Postdoctoral Fellow of the Japan Society for the Promotion of Science (JSPS) at UNU-IAS and the University of Tokyo, Japan, from 2019 to 2021. During her tenure, she worked on climate, biodiversity, and community nexus in socio-ecological production landscapes. From 2016 to 2019, she was Programme Officer in the GEF-GoI-UNDP National Communications Project in the Indian Ministry of Environment, Forest and Climate Change. This position involved preparation of India's National Communications to the UNFCCC, including Biennial Update Reports (BURs). She contributed to India's second and third BURs.

Dr. Gupta received her Ph.D. degree in Environment Science from Panjab University, Chandigarh, in 2015. She is a certified expert in Climate Adaptation Finance. She has 27 research publications in national and international journals and four co-edited books, covering climate policy, forestry, biodiversity, social-ecological systems, and women and climate change. She has been an expert reviewer for many IPCC and IPBES reports.



Dr. Mirza Barjees Baig is Professor at the Prince Sultan Institute for Environmental, Water, and Desert Research, King Saud University, Saudi Arabia. He earned his MS degree in International Agricultural Extension in 1992 from the Utah State University, Logan, Utah, USA, and was placed on the "Roll of Honor". He completed his Ph.D. in Extension for Natural Resource Management from the University of Idaho, USA, and was honored with the "1995 outstanding graduate student award". He has published extensively on the issues associated with natural resources in national and international journals. He has also made oral presentations about agriculture and natural resources and the role of extension education at various international conferences. Food waste, water management, degradation of natural resources, deteriorating environment, and their relationship with society/community are his areas of interest. He has attempted to develop strategies to conserve natural resources, promote the environment, and develop sustainable communities. He started his scientific career in 1983 as a researcher at the Pakistan Agricultural Research Council, Islamabad, Pakistan. He served at the University of Guelph, Ontario, Canada, as Special Graduate Faculty from 2000 to 2005. He served as Foreign Professor at the Allama Iqbal Open University (AIOU), Pakistan, through the Higher Education Commission from 2005 to 2009. He served as Professor of Agricultural Extension and Rural Society at the King Saud University, Saudi Arabia, from 2009 to 2020. He serves as well on Editorial Boards of many international journals and is a member of many international professional organizations.

Dr. Ijaz Rasool Noorka is Professor and Chairman in the Department of Plant Breeding and Genetics, Manager, Research Operations and Farms and Diversified Administrative Assignments at Ghazi University, Dera Ghazi Khan, Pakistan. Prior to this, he served in the Government of Punjab agriculture sector in multiple positions and University of Sargodha as Principal, Director Public Relations and Publications, Chairman, PBG, and Member Syndicate. He received an early education from countryside school of district Jhang, Pakistan, and lastly the postdoctorate from the United Kingdom (UK). He was honored with Roll of Honor (twice), University Color (thrice). He is recognized as an international scientist, innovative thinker with practical solution-oriented outlook. He was invited to represent his research findings throughout the globe, particularly in FAO (United Nation), Japan, China, Morocco, Iran, Turkey, Egypt, South Africa, India, Abu Dhabi (twice), Saudi (thrice), Sri Lanka, Italy, France, Singapore, Malaysia, Sudan, Dubai (thrice), United Kingdom, etc. His credit includes international player, project collaborator (university–industry linkage programs), radio, TV anchorperson, having 250 national and international publications and thirteen book chapters mostly published by Springer and CRC Taylor and Francis.

Contributors

Adnan N. College of Materials Engineering, University of Babylon, Babylon, Iraq

Afzaal Muhammad Research and Development Division, Pakistan Meteorological Department, Islamabad, Pakistan

Ahmad Irfan Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan

Ahmad Mushtaq Department of Plant Sciences, Quaid-I-Azam University, Islamabad, Pakistan;
Pakistan Academy of Sciences, Islamabad, Pakistan

Ahmad Tasneem General Department of Plant Protection (DPP), Karachi, Sindh, Pakistan

Al-Omran Abdulrasoul Department of Soil Science, King Saud University, Riyadh, Saudi Arabia

Aldabbagh Balqees Applied, Science Department, University of Technology, Baghdad, Iraq

Alesa Hanaa College of Materials Engineering, University of Babylon, Babylon, Iraq

Ali Syed Shujat Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Sargodha, Pakistan

Ali Syeda Maria Department of Environmental Science, Faculty of Basic and Applied Sciences, International Islamic University, Islamabad, Pakistan

Anwar Maqsood Faculty of Forestry, Range Management and Wildlife, Pir Mehr Ali Shah Arid Agriculture University Rawalpindi, Rawalpindi, Pakistan

Arévalo Constanza Fauna Australis Conservation Laboratory, School of Agriculture and Forestry, Pontificia Universidad Católica de Chile, Santiago, Chile

Ashraf Kamran Department of Food Sciences, Government College University, Faisalabad, Sahiwal Campus, Pakistan

Asif Muhammad Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan

Aslam Sehrish Department of Environmental Sciences, Faculty of Basic and Applied Sciences, International Islamic University, Islamabad, Pakistan

Auda Jabbar Briahi College of Materials Engineering, University of Babylon, Babylon, Iraq

Aziz Ali Mountain Societies Research Institute (MSRI), University of Central Asia (UCA), Khorog, Tajikistan

Aziz Irfan Dr. Muhammad Ajmal Khan Institute of Sustainable Halophyte Utilization, University of Karachi, Karachi, Pakistan

Aziz Sandra Arifin IPB University, Bogor, Indonesia

Bader Mohammad Katbeh International Phytosanitary Expert, Amman, Jordan

Baig Mirza Barjees Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riyadh, Kingdom of Saudi Arabia

Behnassi Mohamed Senior Environmentalist Expert, Economic Social & Environmental Council (ESEC), Rabat, Morocco;
Director, Center for Environment, Human Security and Governance (CERES), Rabat, Morocco;
Economic Social & Environmental Council (ESEC), Center for Environment, Human Security and Governance (CERES), Rabat, Morocco

Belgacem Azaiez Ouled Food and Agriculture Organization (FAO), Riyadh, Kingdom of Saudi Arabia;
Sustainable Rangeland Management, Food and Agricultural Organization of the United Nations, Riyadh, Saudi Arabia;
Food & Agriculture Organization of the United Nations (FAO), Riyadh, Saudi Arabia

Bonacic Cristián Fauna Australis Conservation Laboratory, School of Agriculture and Forestry, Pontificia Universidad Católica de Chile, Santiago, Chile;
School of Veterinary Medicine and Center for Intercultural Research (CIIR), Pontificia Universidad Católica de Chile, Santiago, Chile

Cressman Keith Plant Production and Protection Division, Food and Agriculture Organization (FAO), Rome, Italy

Deafalla Taisser H. H. Institute of Photogrammetry and Remote Sensing, University of Dresden, Dresden, Germany

Efio Sylvain Center for Research in Economics, Université Saint-Louis, Brussels, Belgium;
Laboratory of Sociology and Rural Extension, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

El-Juhany Loutfy Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riyadh, Saudi Arabia

Gupta Himangana Sustainable Landscapes and Restoration Program, World Resources Institute (WRI), Mumbai, India

Habiyaremye François M. Royal Belgian Institute of Natural Sciences (RBINS), Brussels, Belgium

Hafeez-Ul-Hassan Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Sargodha, Pakistan

Hamaide Bertrand Center for Research in Economics, Université Saint-Louis, Brussels, Belgium

Hmaizah O. College of Materials Engineering, University of Babylon, Babylon, Iraq

Hopmans Jan W. Soil Science and Irrigation Water Management, University of California, Davis, Davis, USA

Houinato Marcel R. B. Laboratory of Applied Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

Ibarra José Tomás Fauna Australis Wildlife Conservation Research Laboratory, School of Agriculture and Forest Sciences and ECOS (Ecosystem-Complexity-Society) Co-Laboratory, Center for Local Development (CEDEL), Center for Intercultural and Indigenous Research (CIIR), Villarrica Campus, Pontificia Universidad Católica de Chile, Villarrica, Chile;
Cape Horn International Center for Global Change Studies and Biocultural Conservation (CHIC), Puerto Williams, Chile & Center of Applied Ecology and Sustainability (CAPES), Santiago, Chile

Islam Aneeza Department of Environmental Sciences, Faculty of Basic and Applied Sciences, International Islamic University, Islamabad, Pakistan

Jibran Rubina Terrestrial Biosciences New Zealand Limited, Auckland, New Zealand;
The New Zealand Institute for Plant and Food Research Limited, Auckland, New Zealand

Karamkhudoeva Munira Pamir Biological Institute (PBI) Khorog GBAO, Khorog, Tajikistan

Keusgen Michael Philipps University, Marburg, Germany

Khan Zafar Iqbal Department of Botany, University of Sargodha, Sargodha, Pakistan

Komal Nayab Department of Environmental Sciences, The University of Lahore, Lahore, Pakistan

Ladan Suleiman Iguda Department of Basic and Applied Sciences, Hassan Usman Katsina Polytechnic, Katsina, Katsina State, Nigeria

Laker Jerry Kod Kod Field Research Station, La Araucanía, Chile

Magnon Yves Z. Laboratory of Sociology and Rural Extension, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

Majeed Salman Department of Plant Sciences, Quaid-I-Azam University, Islamabad, Pakistan

Manzoor Emran Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Sargodha, Pakistan

Marikkar Nazrim National Institute of Fundamental Studies, Kandy, Sri Lanka

Mujeeb Amtul Dr. Muhammad Ajmal Khan Institute of Sustainable Halophyte Utilization, University of Karachi, Karachi, Pakistan

Musthafa Muneeb M. Department of Biosystems Technology, Faculty of Technology, South Eastern University of Sri Lanka, University Park, Sri Lanka

Nawaz Muhammad Farrakh Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan

Nazir Saba Department of Environmental Sciences, The University of Lahore, Lahore, Pakistan

Noorka Ijaz Rasool Department of Plant Breeding and Genetics, University College of Agriculture, University of Sargodha, Punjab, Pakistan;
Department of Plant Breeding and Genetics, Ghazi University, Dera Ghazi Khan, Pakistan

Ochi John E. Department of Agricultural Economics, Abubakar Tafawa Balewa University, Bauchi, Nigeria

Omrane Marwa Ben National Agronomic Institute of Tunisia (INAT) and Mediterranean Agronomic Institute of Montpellier (CIHEAM/IAMM), Montpellier, France

Osunderu Oluwakemi Forestry Research Institute of Nigeria (FRIN), Ibadan, Nigeria

Rais Muhammad Department of Wildlife Management, Pir Mehr Ali Shah Arid Agriculture University Rawalpindi, Rawalpindi, Pakistan

Rajpar Muhammad Nawaz Department of Forestry, Faculty of Life Sciences, Shaheed Benazir Bhutto University, Sheringal, Upper Dir, Pakistan

Ramachandran Nira Gurgaon, India

Rashid Muhammad Haroon U. Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan;
College of Forestry, Fujian Province, Fujian Agriculture and Forestry University Fuzhou, Fuzhou, PR China

Reed Michael Robert Professor Emeritus of Economics, University of Kentucky, Lexington, USA

Sabbahi Rachid Laboratory of Plant Biotechnology, Higher School of Technology, University of Ibn Zohr of Agadir, Laayoune, Morocco

Sadia Haleema Department of Plant Sciences, Quaid-I-Azam University, Islamabad, Pakistan

Shaheen Mehak Department of Forestry, Range and Wildlife, Ghazi University, Dera Ghazi Khan, Pakistan

Sinsin Brice A. Laboratory of Applied Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

Sogbohossou Etotépé A. Laboratory of Applied Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

Sultana Shazia Department of Plant Sciences, Quaid-I-Azam University, Islamabad, Pakistan

Tahir Jibran Terrestrial Biosciences New Zealand Limited, Auckland, New Zealand;
The New Zealand Institute for Plant and Food Research Limited, Auckland, New Zealand

Tossou Rigobert C. Laboratory of Sociology and Rural Extension, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

uz Zaman Qamar Department of Environmental Sciences, The University of Lahore, Lahore, Pakistan

Yaseen Ghulam Department of Plant Sciences, Quaid-I-Azam University, Islamabad, Pakistan;
Department of Botany, Science and Technology Division, Township Campus, University of Education, Lahore, Pakistan

Zafar Muhammad Department of Plant Sciences, Quaid-I-Azam University, Islamabad, Pakistan

Zaman Ezekiel Y. Forest Research Institute of Nigeria, Trial Afforestation Research Station, Kaduna, Nigeria

Abbreviations and Acronyms

AFTs	Agroforestry trees products
AKF	Aga Khan Foundation
BAU	Business as usual
BNF	Biological N Fixation
CA	Conservation agriculture
CAL	Cocoa agroforestry landscapes
CBR	Central Board of Revenue
CDA	Capital Development Authority
CEC	Cation-exchange capacity
CERES	Center for Environment, Human Security and Governance
CFCs	Chlorofluorocarbons
CRU	Climate Research Unit
CSA	Climate smart agriculture
CSL	Consumer surplus loss
CSSVDP	Cocoa Swollen Shoot Virus Disease Program
CT	Conventional tillage
CTF	Powder form
CTO	Coconut Testa Oil
DAAD	German Academic Exchange Service
DLIS	Desert Locust Information Service
DSC	Differential scanning calorimetry
ECTPP	Emergency Centre established for Transboundary Plant Pests
EIA	Environmental Impact Assessment
EWFs	Edible wild fruits
FC	Field capacity
FEWSNET	Famine Early Warning Systems Network
FRAP	Ferric reducing antioxidant power
FYM	Farmyard manure
GBAO	Gorno-Badakhshan Autonomous Oblast
GDLA	Global Dryland Alliance Countries
GHGs	Greenhouse gases

GLOFs	Glacial lake outburst floods
GM	Green manuring
ICRAF	International Centre for Research in Agroforestry
IEE	Initial Environmental Examination
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
KSA	Kingdom of Saudi Arabia
LPG	Liquefied petroleum gas
MAPs	Medicinal and Aromatic Plants
MDGs	Millennium Development Goals
MDS	Minimum Data Set
MHAs	Mountainous and hilly areas
MINADER	Ministry of Agricultural and Rural Development, Cameroon
NBSAP	National Biodiversity Strategy and Action Plan, Pakistan
NCCP	National Climate Change Policy, Pakistan
NGOs	Non-governmental organizations
NSP	Plant Production and Protection Division
NTFPs	Non-timber forest products
NWFP	Non-wood forest products
OER	Office of Emergencies and Resilience
PAM	Polyacrylamide
PMD	Pakistan Meteorological Department
PPAF	Pakistan Poverty Alleviation Fund
PPS	Population proportional to size
RRA	Rapid rural appraisal
RS	Remote sensing
SAPs	Superabsorbent polymers
SDGs	Sustainable development goals
SEPA	State Environmental Protection Agency, Nigeria
SOC	Soil organic carbon
SRWC	Salt Range Wetlands Complex
SVDP	Soon Valley Development Program
SWAC	Desert Locust in South-West Asia
TBTTP	Ten Billion Trees Tsunami Program, Pakistan
TEAC	Trolox equivalent antioxidant capacity
TMPs	Traditional medicine practitioners
TPL	The plant list
TPS	Tribal protection system
UNRISD	United Nations Research Institute for Social Development
USAID	US Agency for International Development
VPD	Vapor pressure difference
WEF	Water–energy–food
WF	Wheat flour

WFP	World Food Programme
WUE	Water use efficiency
WWF	World Wide Fund for Nature

List of Figures

Some Physiological Plant Characteristics to Adapt to the Changing Climate in Indonesia

Effects of Climate Change on Insect Pollinators and Implications for Food Security — Evidence and Recommended Actions

Fostering the Sustainable Forest Management in Saudi Arabia from Resilience and Mitigation Perspectives

Human–Wildlife Conflict: The Case of Crop Raiding and Its Socio-economic Implications Around Pendjari Biosphere Reserve, Northern Benin

Human Activities as a Potential Risk to the Sustenance of Barawa Forest Reserve in Katsina State, Northern Nigeria

Non-timber Forest Product Income: What Implications for Social Safety-Nets in Afaka Forest Reserve Communities, Kaduna-Nigeria?

Potential of Baobab (*Adansonia digitata* L.) in Adaptation to the Environmental Change

Managing the Soil Erosion Through the Use of Polyacrylamide: An Empirical Study

List of Tables

Human–Wildlife Conflict: The Case of Crop Raiding and Its Socio-economic Implications Around Pendjari Biosphere Reserve, Northern Benin

Human Activities as a Potential Risk to the Sustenance of Barawa Forest Reserve in Katsina State, Northern Nigeria

Non-timber Forest Product Income: What Implications for Social Safety-Nets in Afaka Forest Reserve Communities, Kaduna-Nigeria?

Potential of Baobab (*Adansonia digitata* L.) in Adaptation to the Environmental Change

Realizing Food Security in Saline Environments in a Changing Climate: Mitigation Technologies

Crop Diversification Using Saline Resources: Step Towards Climate-Smart Agriculture and Reclamation of Marginal Lands

Land Use Land Cover Change in Salt Range Wetlands Complex of Pakistan in Response to Climate Change

Managing the Soil Erosion Through the Use of Polyacrylamide: An Empirical Study

The Food Security, Biodiversity, and Climate Nexus—Introduction

Mohamed Behnassi, Himangana Gupta, Mirza Barjees Baig, and Ijaz Rasool Noorka

Abstract Ensuring domestic food security was a permanent challenge for various countries at different levels of their development since the 1900s. Today, this challenge, which is still haunting the Global South that uses just 20% of the resources with 80% of world's population, is further compounded by the impacts of climate change, ecosystem degradation, and biodiversity loss on food systems. While implications vary across regions, with some countries benefitting and some disadvantaged, the nexus between these areas will play a major role in shaping the economic, social, and environmental future of the world. Against this background, this volume has been shaped to help collate many case studies relevant to the food security, biodiversity, and climate nexus from different parts of the world, in order to gain both region-specific and a broader global understanding of what issues are most pertinent from the nexus lens. What makes this book unique is the focus on sub-nexuses and their implications for other sectors such as health, nutrition, and traditional practices. Instead of providing only modern science-based solutions for the nexus-related challenges, this volume covers case studies that present mixed solutions, offering the use

M. Behnassi (✉)
Senior Environmentalist Expert, Economic Social & Environmental Council (ESEC), Rabat, Morocco
e-mail: behnassi@gmail.com

Director, Center for Environment, Human Security and Governance (CERES), Rabat, Morocco

H. Gupta
Sustainable Landscapes and Restoration Program, World Resources Institute (WRI), Mumbai, India
e-mail: himangana@gmail.com

M. B. Baig
Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riyadh, Saudi Arabia
e-mail: mbbaig@ksu.edu

I. R. Noorka
Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Sargodha, Pakistan
e-mail: ijazphd@yahoo.com

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_1

of traditional ecological knowledge in combination with modern science for both resilience and sustainability.

Keywords Biodiversity loss · Climate change impacts · Food security · Global south · Nexus · Resilience · Sustainability

1 The Volume's Background, Scope, and Objectives

"Humankind is facing a perfect storm of climate change, biodiversity loss and multiple forms of malnutrition (stunting, wasting, micronutrient deficiencies and obesity) coexisting in the same country, community, household and even individual" (FAO 2021). Indeed, despite the achievements made by human societies in many areas, such as science, technology, and social organization, securing food is still an essential condition for both security and development around the globe. In a context marked by globalizing dynamics, a health crisis, increased environmental disruptions, biodiversity loss, and climate change, enhancing food and nutrition security in a sustainable and resilient way is still a significant challenge. This is further compounded by the complex interlinkages among the various factors affecting the ability of nations to ensure a future free from hunger and malnutrition. According to FAO (2021), food remains the single strongest lever to optimize human health and environmental sustainability on Earth but currently works against both. Changing this will require shifts in demand for food to increase biodiversity in production systems that are environmentally and socially sustainable and resilient to climate change.

Challenges from each of these areas are well known and recognized. Regarding climate change, it is increasingly perceived as a 'direct existential threat', and the scientific community has already called for the world to act swiftly and robustly to limit further warming of the atmosphere. However, the climate action is still out of step with existing scientific data. In addition, biodiversity loss is well documented, although this tends largely to overlook loss of genetic diversity in crops, livestock, poultry, and fish that are farmed, focusing more on headline species facing extinction (FAO 2021).

Biodiversity, supported by healthy ecosystems, is highly connected with food security in many ways and represents a prerequisite for human food, be it wild, cultivated or domestic. Therefore, achieving food security while conserving biodiversity and ecosystem services are two, strongly linked challenges fundamental to securing global sustainability (Collier et al. 2018). More specifically, through the services provided by ecosystems, the nature contributes to the sustenance of human existence and welfare and provides the key foundation for food systems. Moreover, biodiversity contributes to the regulation of the nutrient cycle and the provisioning of clean water and diverse food supply in addition to the mitigation of climate change. However, despite these vital roles, biodiversity at all levels, including the diversity of genes, species, and ecosystems, is progressively lost at alarming rates due to natural and anthropogenic factors. Critical factors include over-exploitation, land-use change, habitat destruction, the uncontrolled spread of alien species, pollution, nitrogen deposition, shifts in precipitations and temperatures, and extreme events (Cramer et al.

2017). This biodiversity loss entails many implications for the nations' capacity to ensure sustainability, resilience, and human security in the future.

In the same vein, what seems to be missing in many development and policy circles is a recognition that food is at the center of climate and biodiversity issues since it is currently threatening both people and planet. Crop and livestock production occupy about half of the world's habitable land surface and consume about three-quarters of the world's freshwater resources. About three-quarters of deforestation—currently running at about 5 million hectares a year—is driven by agriculture, particularly clearing forest to plant crops or raise livestock, driving biodiversity loss, and contributing to climate change (FAO 2021).

In a recent review conducted by the FAO, it was found that the majority of tools and policies on climate change, biodiversity, or food and nutrition security focus on only one or two of these domains and very few explicitly address all three (FAO 2021). However, as illustrated in Fig. 1, if biodiversity within and across terrestrial, marine, and other aquatic ecosystems is protected and promoted as the foundation for food systems and healthy diets through agro-ecological, people-centered approaches, then a wider range of sustainable production systems (agriculture, forestry and fishery) will be incentivized; as a result, a variety of safe and nutritious foods will be made more accessible and affordable throughout the year. Moreover, according to Fongar et al. (2021), the food system is a very complex framework, which needs multi-sectoral thinking and collaboration. Adding biodiversity and climate change to such a framework may be a source of more complexity, but ignoring these two factors may also be a source of more vulnerability and disruptions.

From a scientific perspective, while traditionally the issues of food, biodiversity, and climate change were addressed separately, a growing literature has recently begun to specifically investigate the linkages between them. Linking these areas from a research and policy perspective, managing related trade-offs, and seeking synergies between them are likely to generate multiple co-benefits from sustainability, resilience, development, and security perspectives. Response mechanisms developed from such a perspective will help protect and enhance biodiversity, foster food and nutrition security while boosting mitigation and adaptation.

Against this background, this contributed volume attempts to provide a comprehensive understanding of the linkages and interdependencies between food security, biodiversity, and climate change. Based on a multi-regional and cross-sectoral analysis, the approach consists of assessing the different natural and anthropogenic factors currently affecting ecosystems and their services, especially the impacts of environmental and climatic changes; highlighting the different linkages between the state of biodiversity and food systems in many contexts and scales; and exploring and assessing the effectiveness of various response mechanisms to effectively manage the implications of such linkages. The volume is based on a holistic approach, which is currently necessary, as the dynamics in one area of the nexus may have impacts on the others and a traditional sectoral approach, attempting to manage these areas independently, may endanger sustainability, resilience, and human security in one or more of the other areas. This can result in painful inter-sectoral trade-offs and make it more difficult to find collaborative solutions. In transboundary settings, it

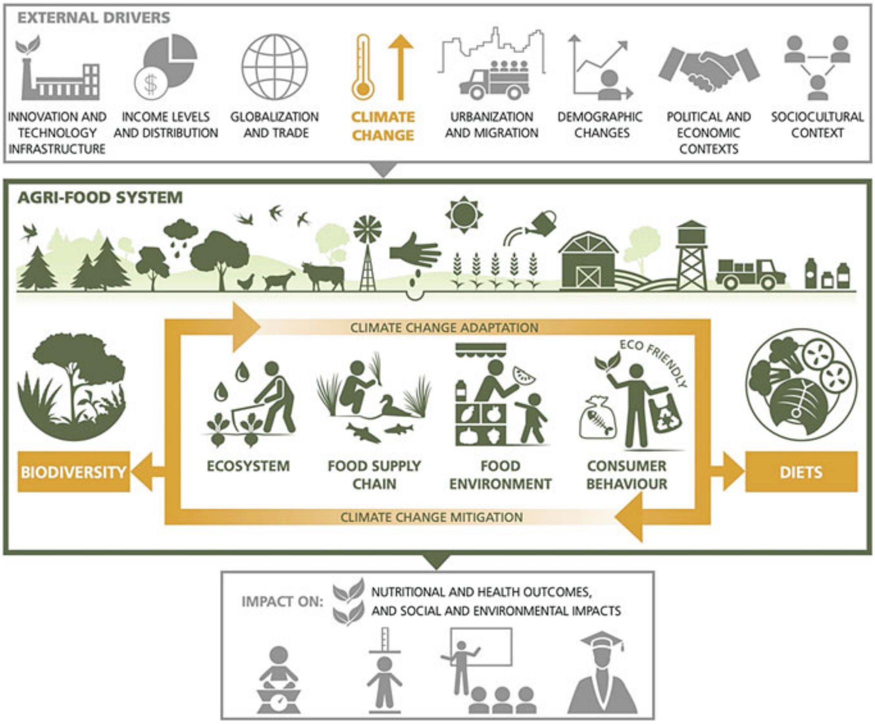


Fig. 1 Theory of change—climate change, biodiversity, and nutrition nexus. *Source* Adapted from HLPE (2020)

may even lead to tensions between countries, thus impeding regional development or generating conflict.

Seventy-three authors from various regions and disciplines contribute to this publication, and most chapters are based on empirical research, particularly done in the Global South (Asia, Africa, and Latin America), and provide inputs for future relevant research and policy agendas.

2 The Volume's Content

This volume is a collation of nexus-specific case studies from different parts of the world presenting both regional and global perspectives on the most pertinent nexus issues. It covers various sub-nexuses and their implications for other sectors—such as health, nutrition, and traditional practices—while providing apt solutions that pave way toward transformation, urgent action, sustainability, and resilience.

In Chapter "Managing the Food Security, Biodiversity, and Climate Nexus: Transformative Change as a Pathway", Behnassi and Gupta claim that the current global climatic and environmental crises are closely interlinked and are the manifestation of the shift to the Anthropocene era, in which the anthropogenic activity has a dominant impact on planetary processes. According to the authors, food systems are increasingly regarded as a key driver of these crises. Not only food production is destroying ecosystems and biodiversity and emitting more greenhouse gas emissions, it also reduces the carbon sequestration capacity of forests, thus exacerbating climate change. To reverse such trends, the authors call for transforming the ways according to which food systems interact with both natural and climate systems. To this end, the quest for transformational change can be mediated by many ways, and available evidence shows that there is a need for a wide range of approaches and methods to tackle the challenges of sustainability and resilience. Building on this approach, the authors attempt in their research to understand the food-biodiversity-climate nexus, present transformative change and its elements as a possible pathway to tackle the complexities of this nexus, identify the various barriers with the potential to hinder the transformative change process, and demonstrate how such barriers, especially those linked to governance, can be eliminated or reduced for an effective transformation.

In Chapter "The Importance of Protected Areas in Mitigating Climate Change and Conserving Ecosystems in Latin America and the Caribbean", Bonacic et al. recall that this region holds 60% of global terrestrial life, but under a changing climate, the conservation of this rich biodiversity is becoming a significant challenge. The authors claim that protected areas may help face such a challenge since they offer opportunities to conserve unique biodiversity, provide ecosystem services, and mitigate climate change effects. Indeed, LAC's contribution to carbon capture, by protecting extensive forests and other natural ecosystems, is potentially opening tremendous economic opportunities under the green economy paradigm. Besides, LAC's protected areas, whose number is increasing in the region, cover almost all types of terrestrial and marine ecosystems. Based on this, the authors describe in their research the current status of protected areas in LAC and explains how this conservation mechanism should play a mitigation role. However, the authors show that although protected areas mitigate the effects of climate change on biodiversity, climate change and traditional environmental problems like deforestation, mining, and agriculture affect the viability of such a conservation mechanism. Thus, the expansion and connectivity of protected areas throughout the region are crucial to combat climate change and biodiversity loss. In addition, the rich biodiversity, in LAC's unique ecosystems, is spatially correlated with rich cultural diversity. This grants opportunity for local and Indigenous communities to participate in managing protected areas in the ecosystems they inhabit.

In Chapter "Impacts of Climate Change on Biodiversity Resources, Especially Forests, and Wildlife Distribution", Rajpar et al. evoke that climate change has direct and indirect impacts on forest vegetation structure and wildlife distribution, therefore seriously threatening biodiversity, particularly forests and wildlife resources. Given the sensitivity of wildlife to climatic factors—such as temperature, evapotranspiration, light intensity, and relative humidity—which alter the distribution of vegetation and the shape of habitat that supports the broad range of wildlife species, climate change negatively disturbs forestry ecosystem functions by affecting productivity, biomass, and trophic interactions. It intensifies the natural balance of flora composition and vegetation structure, which ultimately affects the distribution of home ranges and habitat use of wildlife species. For the authors, determining the impacts of climate change on forests and wildlife resources is of paramount importance since it provides insight into how these various factors affect biodiversity resources. In addition, it will assist in formulating an appropriate strategy for the management and conservation of forest and wildlife resources.

In Chapter "Climate Change and Disappearing Habitats: The Case of Majuli Island in Northeast India", Ramachandran focuses on the case of Majuli Island in Northeast India given its high vulnerability to extreme events, mainly seasonal flooding and erosion, currently worsened by climate-induced impacts which have speeded up the process. This world's largest riverine island is now faced with the threat of imminent extinction which may cause its disappearance within the next two decades. Despite the ancestral adaptive capacity of the original inhabitants of the island to annual monsoon flooding and flood-created losses, they are becoming increasingly helpless in the face of the magnitude of events, which is now destroying the island and sweeping away crops, livestock, and entire villages into the waters. The author claims that the rapidly changing and volatile climate, unwittingly augmented by well-meant but misguided developmental interventions, has led to increasing tensions and conflicts between the inhabitants and officials and between humans and animals. With the loss of their homes and lands, the only option for this subsistence agricultural community is to move to refugee camps, squatter settlements or to mainland towns to earn a livelihood for which they are ill prepared. According to the author, Majuli is a prime example of the need for localizing climate mitigation and adaptation processes and provides a formidable challenge if this is to be accomplished in time to save this unique natural and cultural habitat.

In Chapter "Impacts of Climate Change on Biodiversity in Pakistan: Current Challenges and Policy Recommendations", Anwar et al. focus on the case of Pakistan, which is home to a significant biodiversity given its location at the crossroads of three zoogeographic regions with great altitudinal variation and diversity of ecological zones. However, the authors worry about the sustainability of this biodiversity because it is increasingly threatened by climatic changes. They highlight recent trends in climate change at the global, regional, and local levels and provide an overview of its possible impacts on ecosystems and biodiversity with special reference to the area of study. The analysis has also identified many gaps in existing institutional and policy mechanisms relevant to these areas. Based on the findings, the authors recommend many measures that can help improve communities' adaptive capacities and contribute to climate mitigation and biodiversity conservation, including designing and implementing a strong community awareness program along with capacity building of relevant departments; extending and managing the buffer zone and providing incentives to local communities living around protected areas; establishing corridors and maintaining connectivity with nature reserves in the mountainous areas; systematic afforestation and restoration of degraded ecosystems, and enhanced research on the response of different plant and animal species to climate change. In addition, the authors emphasize the need to consider some specific sectors—such as agriculture and resource extraction—and to monitor policies that address climate change but could negatively impact biodiversity and local communities.

In Chapter "Some Physiological Plant Characteristics to Adapt to the Changing Climate in Indonesia", Aziz evokes the fact that, due to climate change, the country has experienced, in the last 30 years, a significant warming trend, changing rainfall patterns, a reduced seasonality, and recurrent natural disasters such as drought and flood, high humidity, soil degradation, low pH, and decreasing soil organic matters. Moreover, climate change influences plants and adaptations due to the changes affecting the biophysical environment for species survival. More specifically, extreme weather, like high rainfall and strong winds, is advantageous to some perennials but may be disastrous to most annual plants, such as the essential paddy rice agriculture. Based on this context, the author provides background information on these dynamics and suggests some physiological plant characteristics to adapt to climate change in Indonesian tropical agro-systems.

In Chapter "Effects of Climate Change on Insect Pollinators and Implications for Food Security—Evidence and Recommended Actions", Sabbahi recalls the crucial importance of pollinators to biodiversity conservation, ecosystem protection, agriculture, and adaptation. In the context of a changing climate, the geographical range and phenology of insect pollinators shift, their interactions with plants and other taxa are altered, and, in some cases, pollination services are reduced. As a result, a decrease in pollination activity clearly affects adequate crop production, thus compromising the food security. According to the author, efforts should, therefore, be directed toward the preservation of pollinators. In the context of Morocco, one solution for improving agriculture and rising its climate resilience is to take an integrated agro-ecological and socioeconomic approach to pollinator conservation. Moreover, monitoring the status and trends of insect pollinators and assessing pollination functions and services are needed to address the potential effects of climate change and inform adaptive management of ecosystems that could help ensure food security and agricultural sustainability. Recommended actions include as well doing more research to fill knowledge gaps, expanding studies to cover a wider range of pollinators, and promoting coordinated follow-up work at the local, regional, and national levels.

In Chapter "Impacts of Climate Change on Food Security and Health: Medicinal and Aromatic Plants (MAPs) in the Pamir Region of Tajik and Afghan Badakhshan", Aziz et al. recall that the valleys of the Pamir Mountains share a rich and common flora, fauna, and geography and their residents, given their remote location and high poverty rates, traditionally relied on local plants for food and treatment of illnesses. This makes evident the strong relation and dependency of Pamir communities on medicinal plants for both food security, livelihoods, and health purposes. As traditional medicine continues to provide health care for remote mountain communities in the Pamirs, the rapidly changing climatic conditions impacting medicinal plant populations in their natural habitats make mountain communities more vulnerable to different ailments and food insecurity. Based on this, the authors attempt to document the impacts of climate change on MAPs and food security, list available

MAPs, their uses as medicine and food, and discuss conservation-related issues in the research area. This empirical work confirms that while MAP resources were abundant in the region 15–20 years ago, these resources are rapidly depleting due to anthropogenic and climatic factors. The Indigenous knowledge of medicinal plants is rapidly declining as well. The authors emphasize that these findings on the potential importance of MAPs should be shared with Indigenous communities, including the effects of their disappearance on both the traditional health and food systems of mountain communities. The authors believe that recording Indigenous knowledge, concerning the use and preparation of medicinal plants, and transferring such knowledge and technology will help protect medicinal plants from extinction as well as preserving and sustaining the endemic culture and practice of herbal medicine.

In Chapter "Burgeoning Desert Locust Population as a Transboundary Plant Pest: A Significant Threat to Regional Food Security", Ahmad et al. consider desert locust as a spectacular example of nature but also a menacing scourge. The breeding area of this species extends from Morocco to Pakistan and India, and unprecedented movement and migration of its population occurred during the current upsurge of 2019–2021. The authors think that the current COVID-19 pandemic, in amalgamation with desert locust, has created an extraordinary situation that has shaken the food security and economy of the whole region. This is happening in a context where the right to food is increasingly considered as a human right and food needs to be permanently available, abundant, and accessible to all. The authors emphasize the current need to find out the prudent ways to fight this scourge by countries' own resources in collaboration with the FAO-based contingency plans. According to the authors, FAO has established the desert locust information service (DLIS), nearly five decades ago, for monitoring, forecasting, and early warning of desert locust in the countries where the crops are under the direct threat of this pest. DLIS has a state-of-the-art technology, a very unique expertise, and field presence with the ability to link up different governments to strengthen their capacities in desert locust management. Therefore, proper control and management of desert locust in the region under direct threat are needed in order to save the crops from damage and ensure food security.

In Chapter "The Potential of Edible Wild Fruits as Alternative Option to Ensure Food Security in a Changing Climate: A Case Study from Pakistan", Sadia et al. claim that food and nutrition insecurity has increased due to a greater sensitivity to shifting climatic conditions and obsolete food production and processing methods. In Pakistan, which is endowed with a rich diversity of edible wild crops, mostly used by food-insecure countries, climate change has negatively impacted both agriculture and such crops, thus threatening the national food security. Based on this context, the authors attempt to screen the nutritional and antioxidant potential of four underutilized edible wild fruits (EWFs) of family Rosaceae, with a special emphasis on their mineral diversity, proximate composition, bioactive compounds, free radical scavenging activity using various assays, and analytical methods to study minerals. The findings show that the Rosaceous WEFs are precious natural source of antioxidant/nutraceuticals as supplementing dietary foods. These fruits are not only a food supplement, but also an important part of food and nutritional security, as well as a viable alternative for the long-term survival. A variety of techniques that may be used to analyze and cope with the negative effects of climate change has been presented by reference to climate-smart agriculture, which can be referred to as an approach that aims to promote sustainable agriculture and ensure food security.

In the same perspective, Marikkar and Muneeb in Chapter "The Potential of Coconut Byproducts to Foster Food Security and Environmental Sustainability in Sri Lanka", consider coconut as an important crop, mainly in the tropical and subtropical regions of the globe. It is one of the top ten useful trees in the world, providing food and non-food benefits to millions of people worldwide. As coconut is the second-largest crop in extent next to staple crop 'rice' in Sri Lanka, it plays a vital role in the household food security. The annual production of coconuts in the country is reported to be about 2.8 billion nuts, out of which 1.8 billion is used for household consumption, and the balance of one billion is being available for manufacture of coconut products. In recent times, factors like climate change, fragmentation of coconut lands, and prevalence of pest and diseases pose major risk for future coconut yield in the country. Maximizing the utilization of the coconut sector's by-products is proposed by the authors as a proactive approach to address coconut-based food insecurity in Sri Lanka. Coconut shell, coconut testa, coconut sap of the inflorescence, and mature coconut water released from factories are some of the by-products of coconut industry, showing great potential according to the authors. Utilizing them for food purposes might entail various direct and indirect economic benefits and positive environmental impacts, while reducing disposal costs and increasing the value of the coconut tree.

In the same vein, Noorka et al. in Chapter "Potential of the Medicinal Flora in Pakistan and the Risk of Extinction: The Need for a Conservation Strategy", focus in their research on the medicinal flora, which has a prime importance since 10% of the known plant species are used to cure human and animal diseases. In the case of Pakistan, large populations depend on plants for their livelihood and for the cure of major and minor diseases and such plants are mostly wild, with some plants cultivated as field crops. However, according to the authors, the important therapeutic flora species are going to be extinct in the country due to many factors, particularly the over-collection by unauthorized people and the lack of a conservation strategy and a proper maintenance system. To face such a problem, the authors recommend the sensitization of local populations on the importance of growing essential medicinal flora. Moreover, the present raw utilization of medicinal herbs in Pakistan and their prime conservation as income resources should be a key concern for research, business, and policymaking.

In a similar perspective, Osunderu in Chapter "Fostering Health Security Through Biodiversity: A Case Study from Ogun and Lagos States, Nigeria", reports that, globally, over three-quarter of the population is using herbal medicines with an increasing trend. According to a recent study, conducted among traditional medicine practitioners (TMPs) in Ogun and Lagos States, Southwest Nigeria, the author claims that there are signs that the climate change impacts are already being felt, not only in terms of temperature increase, but also in respect of the availability of medicinal plants for the treatment of diseases in the forest zone of Nigeria where these states are located. Herbal medicines are beneficial because medicinal plants are used to address the twin challenge of promoting sustainable livelihoods and treating numerous illnesses in Nigeria. Based on this, the author attempts in his research to help understand how TMPs contribute to the social, economic, and political problems posed by climate change in Africa and to identify the processes, methods, and tools which may assist Africans at the grassroots in adapting to and mitigating the effects of climate change. In addition, he outlines some steps which may be taken in order to create a more systematic method of adaptation strategy by organizations and people interested in facing climate risks both in Nigeria and Africa.

In Chapter "Fostering the Sustainable Forest Management in Saudi Arabia from Resilience and Mitigation Perspectives", El-Juhany et al. recall that, globally, the overall health of forest ecosystems is declining due to a wide range of biotic and abiotic factors. In the Kingdom of Saudi Arabia, many natural and anthropogenic factors are influencing forest ecosystems, including high temperatures, overwhelming drought, low and irregular pattern of rainfall, land clearing for urban areas expansion, cultivation of agricultural crops, and cutting fuelwood. This situation is further compounded by the lack of qualified and professional forestry personnel in comparison with the optimum required to implement planned activities and to ensure a sustainable forest resource management. Against this background, the authors identify in this research the factors threatening the sustainability of forest ecosystems and resources and the challenges and issues facing their sustainable management. They conclude with a review of viable options and suitable strategies to assist and work with potential consumers and users of such resources. The purpose is to present the critical analyses based on the available literature, so all stakeholders, including extension staff, foresters, policymakers, and planners, could help ensure the sustainability of forest ecosystems. Moreover, according to the authors, it is important to sustainably manage forest resources by reference to scientific inputs and to foster the community's resilience and their capacity in this area through, for instance, educational and awareness programs.

In Chapter "Human–Wildlife Conflict: The Case of Crop Raiding and Its Socioeconomic Implications Around Pendjari Biosphere Reserve, Northern Benin", Efio et al. claim that human–wildlife conflict is becoming a serious threat for both wildlife conservation and human well-being and its main representations are livestock predation and crop raiding. The authors examine, in this research, the problem of crop raiding by wildlife and its socioeconomic implications around Pendjari Biosphere Reserve in Northern Benin. Crops with the highest degree of destruction, according to this empirical work, are cotton, maize, millet, and sorghum, and the wild animals responsible for this are mainly baboon, warthog, and elephant. Moreover, crop raiding causes, for an average farmer, a considerable annual financial loss if compared to the annual minimum salary in Benin. It is true that farmers try to manage the impacts of crop raiding with various mitigation measures such as guarding, but the authors notice that the heavy toll of crop raiding and the low level of effectiveness of such measures clearly reveal the vulnerability of agricultural households bordering protected areas.

In Chapter "Human Activities as a Potential Risk to the Sustenance of Barawa Forest Reserve in Katsina State, Northern Nigeria", Ladan undertakes an empirical work to establish the link between human activities and their impacts on a forest reserve in the study area. This has been corroborated by the findings which showed that numerous human activities—such as illegal cutting of trees, fires in the reserve set to burn tires or hunt animals, collection of laterites for building purposes, encroachment for building or farming activities, and overgrazing by domestic animals—have posed serious risks to the sustenance of the reserve. According to the author, the effects of such activities on the environment are various and include the loss of wind breakers and the increase in related environmental hazards. It is true that the governments have regularly taken the necessary mitigation measures, but their efficiency in ensuring the conservation and protection is questionable. Therefore, the author recommends that strategies should be adopted to ensure resilience and viability of the reserve against harmful human activities.

From a different perspective, Ochi and Zaman in Chapter "Non-timber Forest Products Income: What Implications for Social Safety-Nets in Afaka Forest Reserve Communities, Kaduna-Nigeria?", analyze the non-timber forest products (NTFPs) in a social safety-nets context as a paradigm shift, which enables to focus on the demand side of forest products as a repository for providing ecological services to society, including food and energy security, medicines, raw materials, and platforms for protecting the cultural heritage as well as leveraging on the safety-nets for poverty alleviation in the communities. In this approach, according to the authors, NTFP income forms the basis for constructing the income inequalities for the six modeled occupations among the two groups of only NTFPs collection and other economic activities with NTFPs collection.

In Chapter "Potential of Baobab (*Adansonia digitata*L.) in Adaptation to the Environmental Change", Deafalla claims that the importance of natural resources in supporting rural livelihoods all over the world was increasingly being recognized in national and international policy, but human well-being is increasingly relying on the ability to sustainably exploit such resources. In other terms, approaches to development are growingly required to enable income generation from natural resources while at the same time supporting their effective conservation. From this perspective, the author investigates, through an empirical work, the importance of baobab tree in non-timber forest produce and adaptation to environmental change and highlights the conflict between national development efforts and a responsible approach to natural resource conservation. According to the findings, drawing on baobab as a multiple value tree for livelihoods strengthens rural people's resilience against the impacts of both environmental change and extreme events. The key to this resilience is to develop viable policy responses and create dynamic innovative research, strategies, management, and policies which focus on local communities to avoid the hazard of marginalizing those who rely on natural resources for subsistence and income generation.

In Chapter "Realizing Food Security in Saline Environments in a Changing Climate: Mitigation Technologies", Tahir et al. assert that the anthropogenic climate change has, in the last 150 years, stimulated the salinization of agricultural lands. Certainly, salt accumulation in groundwater, coupled with extended periods of droughts, a rise in sea levels, and deforestation are key processes that deteriorate agricultural lands. This significantly causes severe damages to farming communities, threatens economic and food independence and habitability of lands, and challenges the survival of planetary biota. Based on this, the authors provide a comprehensive review of major progress made in soil management, plant genetics, molecular sciences, and indoor farming given their importance in the quest to reduce the impact of salinization on crop production.

In the same vein, Aziz et al. in Chapter "Crop Diversification Using Saline Resources: Step Toward Climate-Smart Agriculture and Reclamation of Marginal Lands", recall that massive industrialization, deforestation, and pollution have accelerated land degradation and major crop losses, thus reducing food resources. Climatic changes, coupled with the reduction of freshwater resources, soil salinization, and expanding salinity due to erroneous irrigation techniques have further exacerbated the degradation of productive land. Moreover, countries with arid climates are increasingly prone to food insecurity as a consequence of fluctuating market prices owing to huge rates of food import. Considering these facts, the authors call for effective measures to feed the world population, which would require a well-planned system. In this perspective, the authors highlight the conceivable outcomes of climate-smart agriculture and reclamation of marginal lands by using saline resources. This is corroborated by recent studies which suggest that crop diversification (non-conventional agriculture) using natural saline resources may provide a solution to feed the livestock besides helping in land reclamation. Research on salt- and drought-resisting plants points toward crop halophytism that may assist in achieving essential targets. For the authors, the ability of halophytes to adapt to climatic changes and human activities has been revealed, which could aid in the global fight against hunger. Also, the removal of salts and trace metals, as well as intercropping halophytes with traditional crops for diverse ecological and economic goals on degraded lands, has been studied.

In Chapter "Land Use Land Cover Change in Salt Range Wetlands Complex of Pakistan in Response to Climate Change", Ali et al. emphasize that wetlands, as natural biomes, are threatened globally due to population growth, unsustainable development, and climate change. As a result, a number of wetlands have been replaced to meet the rising food production demand and agricultural practices in the twentieth century. In this chapter, the authors assess the Salt Range Wetlands Complex (SRWC), in the central north region of the Punjab province of Pakistan, to understand the climatic trends of SRWC and spatiotemporal change detection in the area of lakes over the period 1987–2014. Predictive assessment due to changing climate scenarios has also been discussed by the authors. The vulnerability of the area toward natural disasters drew their attention to address this topic in response to giving a high priority to wetlands for achieving the SDGs #2, #6, and #12. In this regard, an increase in the average annual rainfall pattern from the year 1985 to 2014, while a decrease in temperature and potential evapotranspiration, was observed using the Climate Research Unit (CRU) data. The change detection analysis has revealed the increase in agricultural, uncultivated, built-up areas, and water bodies with a reduction in forest and scrub area. Predictions using Representative Concentration Pathways 4.5 and 8.5 have revealed as well a stress on water resources in the future (2010–2050).

In Chapter "Bioresource Nutrient Recycling and Its Relationship with Soil Health Under Irrigated Agro-Ecosystems", Nazir et al. present soil health as an integrative property that reflects the capacity of soil to respond to agricultural intervention, so that it continues to support both the agricultural production and the provision of other ecosystem services. For the authors, however, the important challenge within sustainable soil management is to conserve ecosystem service delivery while optimizing agricultural yields. Moreover, the low fertilizer-use efficiency in most of the fertile soils is another factor which is behind the excessive use of chemical fertilizers, which affects crop growth and soil properties both positively and negatively. Due to the scarcity of mineral—nitrogen, phosphorous, and potassium—and soil resources and food insecurity, the authors believe that the recycling and recovery of resources should be at the center of future efforts. Bioresource management is a well-known and widely accepted practice as a key component of conservation agriculture. However, the improper management of these bioresources often limits their positive effects. In this perspective, the authors reviewed all recent findings to understand and summarize the different aspects of the bioresource management and recycling and their impact on soil health in farming systems, which are linked to the environment and ecology.

In Chapter "Managing the Soil Erosion Through the Use of Polyacrylamide: An Empirical Study", Aldabbagh et al. focus on Polyacrylamide (PAM), which is a water-soluble polymer and highly water-absorbent used to bind soil particles together for gaining stability against water and wind erosion. The authors attempt to study the PAM properties like thermal degradation and melting point by differential scanning calorimetry (DSC). Surface parameters, like roughness, bearing index, core fluid retention index, and valley fluid retention index, were determined by the authors using the atomic force microscopy. The surface runoff for soil stability has been also determined under different conditions by using a spray gun. The same has been done for the weight loss, which was tested for soil stability conclusion. According to the findings, the authors prove that the surface runoff and the weight loss of soil decrease with the increase of PAM concentration.

Building on all chapters presented above, this volume attempts to capture the links, synergies, and trade-offs among food security, biodiversity, and climate change as a step ahead in understanding the complex interlinkages in social–ecological systems. As the reader may notice, investigating the nexus is challenging due to missing links and multiple sub-nexuses that operate at economic, environmental, and social scales. Many related challenges were tackled by the authors, focusing on one nexus at a time and presenting its implications. This increased the extant nexuses covered in this volume, from the links between climate and biodiversity to pests, pollinators and food security, or the importance of traditional and local knowledge, local health baskets, and traditional healing.

The volume equally focuses on the solutions side, covering the relevance of crop diversification, sustainable forest management, protected areas network, community engagement, mitigation technologies, and ecosystem restoration. By focusing on sustainability and resilience, this volume provides a pathway to understanding nexus approaches to build upon transformative change strategies. This may help fill the huge science-policy-practice gap in the nexus areas. Additionally, since this volume has been compiled at a time when such nexuses are being recognized at a global level, we hope it will contribute to ongoing work, including the IPBES nexus assessment, which is currently underway.

References

Collier N, Sayer J, Boedhihartono AK, Hanspach J, Abson D, Fischer J (2019) System properties determine food security and biodiversity outcomes at landscape scale: a case study from West Flores, Indonesia. Land 7:39. http://doi.org/10.3390/land7010039

Cramer W, Egea E, Fischer J et al (2017) Biodiversity and food security: from trade-offs to synergies. Reg Environ Change 17:1257–1259. https://doi.org/10.1007/s10113-017-1147-z

FAO (2021) Climate change, biodiversity and nutrition nexus, in brief. https://www.fao.org/3/cb6087en/cb6087en.pdf

Fongar A, Estrada Carmona N, Lizarazo M, Zakaria MR, Ekesa B (2021) Strengthening the rationale on the nexus of biodiversity-climate change-food and nutrition security in the Small Island Developing States (SIDS) of Samoa and Tonga. Literature review. Alliance of Bioversity International and CIAT, Rome (Italy). https://cgspace.cgiar.org/bitstream/handle/10568/114197/Literature%20review%20report_FAO_SamoaTonga_June%202021-Final.pdf?sequence=1&isAllowed=y

HLPE (2020) Food security and nutrition: building a global narrative towards 2030. A report by the high level panel of experts on food security and nutrition of the Committee on World Food Security, Rome

Managing the Food Security, Biodiversity, and Climate Nexus: Transformative Change as a Pathway

Mohamed Behnassi and Himangana Gupta

Abstract The current global climatic and environmental crises are closely interlinked and are the manifestation of the shift to the Anthropocene era, in which the anthropogenic activity has a dominant impact on planetary processes. In this broad context, food systems are increasingly regarded as a key driver of these crises. Not only food production is destroying ecosystems and biodiversity and emitting more greenhouse gas emissions, it also reduces the carbon sequestration capacity of forests, thus exacerbating climate change. To reverse such trends, we need to transform how food systems interact with both natural and climate systems. To this end, the quest for transformational change can be mediated by many ways, and available evidence shows that we do need a wide range of approaches and methods to tackle the challenges of sustainability and resilience. Building on this approach, this chapter attempts to understand the food-biodiversity-climate nexus, presents transformative change and its elements as a possible pathway to tackle the complexities of this nexus, identifies the various barriers with the potential to hinder the transformative change process, and demonstrates how such barriers, especially those linked to governance, can be eliminated or reduced for an effective transformation.

Keywords Biodiversity loss · Climate change · Ecosystem degradation · Food systems · Transformative change

M. Behnassi (✉)
Senior Environmentalist Expert, Economic Social & Environmental Council (ESEC), Rabat, Morocco
e-mail: behnassi@gmail.com

Director, Center for Environment, Human Security and Governance (CERES), Rabat, Morocco

H. Gupta
Sustainable Landscapes and Restoration Program, World Resources Institute (WRI), Mumbai, India
e-mail: himangana@gmail.com

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_2

1 Introduction

The world is facing multiple crises as manifested in ongoing climatic and environmental disruptions, a global pandemic, and rapidly growing inequality and human insecurity. Climate change and other environmental challenges, such as the loss of ecosystems, mass extinction of species, and global pollutions, have become defining challenges of our time whose impacts are affecting the poorest countries and regions and vulnerable populations in the most severe fashion (Uitto and Batra 2022). These crises are closely interlinked in that their drivers mainly reside in human activity. They are the manifestation of the shift to the Anthropocene era, in which human activity has a dominant impact on planetary processes. In this era, humans try to continuously reconstruct and control their environment, the limits of which are visible in the repeated disruptions that it undergoes with increasing intensity (Barrière et al. 2019). We do stand at the edge of planetary boundaries very aptly defined by Rockström et al. (2009), and our current development trajectory is entirely unsustainable, which is endangering the prosperity of both current and future generations. We therefore need to transform how we interact with natural systems. To this end, the quest for transformational change for the people and the planet can be mediated by many ways, and available evidence shows that we do need a wide range of approaches and methods to tackle the challenges of sustainability and resilience (Uitto and Batra 2022).

During the 2000s, the international context has changed rapidly. Most countries have adhered, among others, to the 2030 Agenda for Sustainable Development, the attendant Millennium and Sustainable Development Goals (MDGs, SDGs), and to the Paris Agreement on Climate Change. The 2030 Agenda recognizes that sustainability depends equally on three interlinked pillars: social, economic, and environmental. All SDGs for instance incorporate each of these dimensions to a varying degree. If one of the dimensions fails, the goal is not achievable (Uitto and Batra 2022). In general terms, these interrelated frameworks provide a common understanding of the universal priorities and the sense of urgency of transforming the way our societies operate. They call for a new value system that is not based only on measuring economic growth, but emphasizes sustainability, resilience, and equality. They also recognize the existential threats that humankind faces due to anthropogenic climate change and environmental degradation (Uitto and Batra 2022).

In this broad context, food systems are increasingly regarded as both a factor and a key solution to the above-mentioned crises. Indeed, food production is one of the main sources of carbon emissions and causes of environmental destruction today. Land is continuously cleared for agriculture and cattle raising, and we lose some 12 million hectares of tropical forest each year primarily due to land conversion for agriculture and other economic activities. Not only does this destroy ecosystems and animal and plant species therein, it also reduces the carbon sequestration capacity of forests, thus exacerbating climate change (Uitto and Batra 2022). Therefore, the compulsion to produce more food and expand agriculture to cater to the needs of an increasing population (Ortiz et al. 2021) is detrimental to global sustainability and comes at a time when land-use change is highest, the degradation of ecosystems is faster due to climate change, and the preservation of biodiversity is becoming a high priority (Godfray 2011).

In this regard, many recent significant studies on the water-energy-food (WEF) nexus, which demonstrated and analyzed inherent linkages with climate change (Hasanzadeh Saray et al. 2022; Ogbolumani and Nwulu 2022; Liu et al. 2022) and biodiversity (Stavi et al. 2021; Colman et al. 2022; Ramirez-Contreras et al. 2022), have pointed to the fact the WEF nexus affects the social and economic prospects of a nation through various sub-nexuses that operate. This makes it look more complicated and, thus, needs concerted attention on the nexus interaction dynamics to be able to make a shift in relevant governance frameworks. Accordingly, the food-biodiversity-climate nexus clearly appears as a part of many other existing and broad set of nexuses among and beyond the area of the environment. Therefore, detangling the approach with which these nexuses are usually seen would be a first step to synergize them and to achieve transformational change.

This is in line with a recent Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report, released in the context of COVID-19, which claimed that future pandemics will emerge more often, spread more rapidly, kill more people, and impact the global economy unless a transformative change is initiated to address these infectious diseases (Daszak et al. 2020). In fact, the lesson learned from the pandemic made it clear that solutions to many crises and future avoidance will require a transformative, systems approach to reduce the global environmental changes caused by unsustainable production and consumption; these changes drive biodiversity loss, climate change, pollution of oceans, land, and air, and pandemic emergence (GEF 2020). Building on this approach, this chapter attempts to understand the food-biodiversity-climate nexus, presents transformative change and its elements as a possible pathway to tackle the complexities of this nexus, identifies the various barriers with the potential to hinder the transformative change process, and demonstrates how such barriers, especially those linked to governance, can be eliminated or reduced for an effective transformation toward sustainability and resilience.

2 Understanding the Food-Biodiversity-Climate Nexus

Both climate change and biodiversity loss are significant threats for livelihood, food and health security, and the negative impacts of which will be felt disproportionately by marginalized communities (Pörtner et al. 2021). Indeed, climate change is a key driver of change in both biodiversity and food systems with the ability to cause both direct and indirect impacts. Indeed, one of the greatest challenges of our time is the loss of both habitat, ecosystem integrity, and biological diversity. We are currently facing the most rapid loss of biological species in history, earning the moniker 'the sixth extinction' (Uitto and Batra 2022). Also, the ease of the international trade of agricultural products is also a major contributor to biodiversity loss induced by food production impacts (Ortiz et al. 2021). Many species of flora and fauna, under threat by intensive agriculture, are now experiencing added pressures from climate change acting on both humans and ecosystems. Therefore, it is becoming a global challenge to achieve efficient and productive agricultural land use while also conserving biodiversity (Tscharntke et al. 2012) and facing climate risks. Similarly, ocean warming and acidification are causing an unprecedented biodiversity loss and decline in fisheries, which are drivers of more food insecurity, marine ecosystem degradation, and the decline of carbon sequestration potential of marine environment (Turley and Gattuso 2012; Gattuso et al. 2013; Elver and Oral 2021). These examples clearly show the nexus between food security, biodiversity, and climate change while pointing toward the urgency to act in a more transformative manner. Tweaking current governance structures slowly has kept us at the same place where we were when the MDGs were adopted. What was true for the Millennium Ecosystem Assessment is a starker reality today. This means we have not really changed our process and efficiently implemented the appropriate response mechanisms since this process is usually backed by economic gains more than sustainability and resilience goals.

This is high time now where transforming the ways toward sustainability and resilience becomes imperative to avoid irreversible scenarios. However, as the world reaches the tipping points, inequality is rising among and within nations, with extreme lack of policy coherence, making sustainability and resilience itself a challenge.

Within the food-biodiversity-climate nexus, the dynamics work in two directions. On the one hand, the impacts of climate change, biodiversity loss, depleting water and land resources, and, in turn, changing food production patterns would threaten food security. On the other hand, buffering the slow-onset effects of climate change, such as biodiversity loss, desertification, salinization, and land degradation, forests, and rangelands can help ensure food security (Stavi et al. 2021). There are clear opportunities within the challenges that are yet not been thought through and managed in an integrated manner. This could be due to social impediments, financial obstacles, or governance barriers.

To illustrate such dynamics, Fig. 1 shows the various sub-nexuses and key linkages of food, biodiversity, and climate with, for example, water resources, adaptation, agro-diversity, deforestation, and food security. It also shows the global objectives aiming at addressing each of these global issues but with different goals and a non-aligned approach toward other environmental issues and targets. To take an action that manages the nexus, these linkages must be the action footprint in today's world which, to be transformative, must address the sustainability and resilience challenge. The latter increasingly depends on the capacity of the world to deal with food systems' problems, biodiversity loss, and climate mitigation and adaptation. Accordingly, global targets related to major global problems are to be delegated to the nations, which should take the needed domestic actions toward sustainability and resilience.

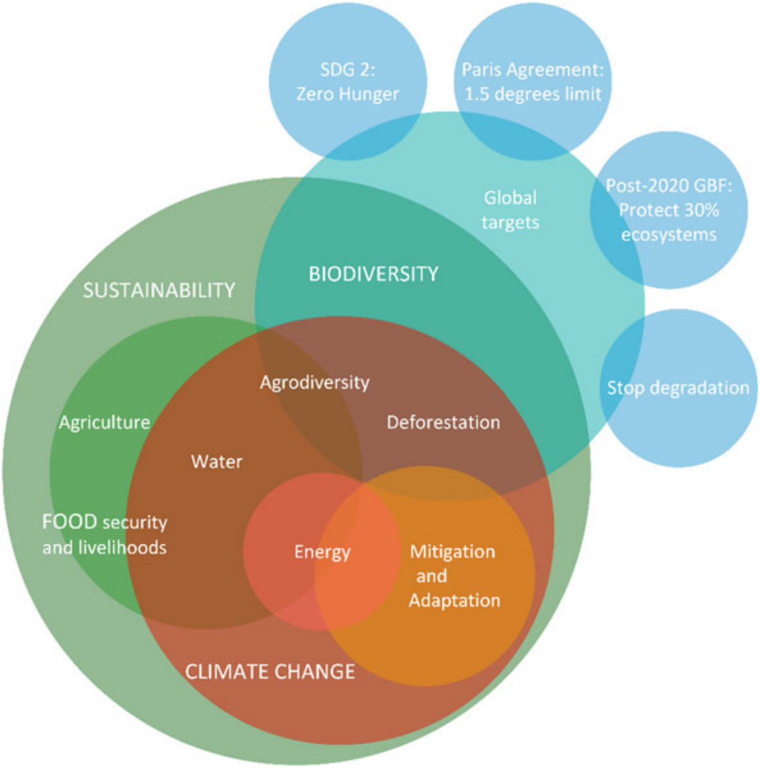


Fig. 1 Sub-nexuses and current non-aligned global targets. *Source* Developed by the authors

The food, biodiversity, and climate nexus' interplay could be different for various regions or countries. For instance, food production is likely to be the main driver of Europe's future landscape change dynamics irrespective of climate change, with cascading effects on forestry, biodiversity, and water under various scenarios (Kebede et al. 2021).

2.1 *Food and Biodiversity Linkages in the Context of Climate Change*

Food production has often been a competitor of biodiversity in terms of land and water use and thus a driver of biodiversity loss (Benton et al. 2021). The conversion of natural land cover for agriculture, that included plantations for timber, pulp, and paper, has been a major cause of emissions from deforestation in countries like Brazil and Indonesia (McLaughlin 2011). Agroforestry, with an objective to enhance biodiversity, can be beneficial for both climate and enhancing livelihoods (Pörtner et al. 2021); however, extracting bioenergy with carbon capture and storage (BECCS) through dedicated herbaceous or woody bioenergy crops and non-native production forests must be avoided as they can damage ecosystems directly or through increasing competition for land (IPCC 2022). Many mitigation-oriented monoculture plantations led to maladaptation, loss of soil quality, while impacting local diversity (Gupta and Dube 2018).

Conventional food systems are also driving climate change as a source of GHG emissions, which negatively impacts biodiversity by degrading habitats and shifting species distribution (Benton et al. 2021). It is true that the on-farm functional biodiversity provides services like pollination and biocontrol (Tscharntke et al. 2012) and a variety of crops for food that is essential for resilient agricultural production (Ortiz et al. 2021); however, with further intensification of agriculture, all services provided by biodiversity for food security are being severely threatened (Tscharntke et al. 2012; Ortiz et al. 2021). Certainly, there is an increased loss of agro-diversity, especially local and traditional varieties, in many biodiversity-rich social–ecological landscapes (Gupta et al. 2021). In addition, climate change may enhance the risk of invasive species in many regions, disrupting biodiversity, and thus food production in the long run (Ortiz et al. 2021).

In the context of a changing climate, future food systems are threatened as highlighted in Sect. 2.2. There have been many examples in the past where crop failure led to countrywide famines with considerable human damage. Just recently in 2010, the drought caused the loss of a quarter of the grain area in Russia, and the flood ruined half a million tons of wheat in Pakistan (Reuters 2010). As climate change brings in more diseases and extreme events, such failures may become common in the future and cause widespread economic loss, social tension, and human displacement. The solution for this lies, among others, in the genetic diversity of wild relatives of our current crops that are increasingly being lost as a result of human-driven disruptions. Biodiversity here is both a solution and a victim in the context of climate change.

2.2 *Food and Climate Change Linkages in the Context of Biodiversity*

The impact of climate change on monsoons, changing temperature patterns, and the loss of agro-diversity due to the intensification of agriculture have increased concerns over the agricultural sustainability. A huge uncertainty currently characterizes the prediction of local impacts of climate change, especially those related to rainfall perturbations, temperature variations, and related socioeconomic implications. Climate change thus complicates the relationship between biodiversity and food production through agriculture. Climate change is likely to surpass or even compound the impacts of land-use change caused by agriculture and other activities in the future (Ortiz et al. 2021).

On the other hand, climate change will impact food systems in various ways, including through direct impact on the yields, slow-onset events, extreme events, and impact on water resources. There is also an increasing demand for forestry activities to deal with climate change that may further risk food security. Throughout the human history, farming systems have generally managed to adapt to climate variability, changing economic conditions, and technology and resource availability and have kept pace with a growing population. While the technological potential to adapt to changes may exist, the socioeconomic capability differs for different types of farming systems (Khan et al. 2009).

The current food systems' patterns seem incompatible with the rising food demand since a large number of people still go hungry. After steadily declining for a decade, world hunger is on the rise, affecting 9.9% of people globally—795 million people according to FAO (2017). From 2019 to 2020, between 720 and 811 million people faced hunger, a crisis driven largely by conflict, climate change, and the COVID-19 pandemic.[1] Ray et al. (2013) already demonstrated, for instance, that the yields of maize, rice, wheat, and soybean are increasing at 1.6%, 1.0%, 0.9%, and 1.3% per year, non-compounding rates, respectively, which is less than the 2.4% per year rate required to double global production and meet projected demands in 2050.

Transformative actions by countries, farmers, researchers, investors, and the private sector are thus needed to tackle the climate change challenge—both adaptation and mitigation—faced by the agricultural sector (Dinesh et al. 2017). In this context, it is equally important to conserve biodiversity that will play a major role in ensuring continued supply of ecosystem services and crop improvement, as and when needed.

3 Transformative Change as a Pathway to Manage the Nexus

Crises often entail opportunities. However, for a crisis to lead to transformation, a viable alternative to the status quo must exist that a large segment of people can align behind (Berman 2020). Also, assuming implicitly that a transformation would be toward something positive is not necessarily the plausible scenario (Uitto and Batra 2022). Transformation has been defined by O'Connell et al. (2016) as a shift from the current system to a substantively new and different one.

In the context of this research, the term 'transformational change' means a change from an unsustainable setting toward a more sustainable, inclusive, resilient, and environmentally sound state. In this perspective, our perception is aligned with the IPBES Global Assessment (IPBES 2019), which defines transformative change as a "fundamental, system-wide reorganization across technological, economic and social factor, including paradigms, goals and values" (IPBES 2019). For the IPBES, there

[1] State of Food Insecurity and Nutrition in the World 2020 online summary, http://www.fao.org/state-of-food-security-nutrition/en/.

are plausible pathways for achieving the 2050 Vision for Biodiversity and other global goals, but these necessitate fundamental changes in development paradigms and social–ecological dynamics. More specifically, these pathways require changes in society, more sustainable use of land, water, energy, and materials, as well as changes in consumption habits, food systems, and global value chains. This includes both individual decisions to help start or build new social norms and the legal and policy shifts that unlock all other kinds of change.

There are several ways through which transformative change can be achieved in the context of food-biodiversity-climate nexus. First, to tackle the food-biodiversity sub-nexus, researchers argue for 'land sharing' (Crespin and Simonetti 2021) that is simultaneously using agricultural landscapes for less-intensive cultivation (sacrificing crop yields) and conservation. Many others support 'land sparing', or maximizing agricultural outputs from some land, in order to allow other land to be set aside for conservation (Godfray 2011). In both cases, nature-based solutions, such as joint mitigation and adaptation, will be practiced in order to integrate several concerns into one initiative, thus providing multiple benefits for food, biodiversity, and climate change (Gupta and Dube 2018, 2021).

Having conservation criteria is another way to foster transformative change. As the demand for agricultural products rises, land expansion will occur, but the conditions under which this should happen must be defined. This could be based, for example, on conservation standards that restrict any conversion of land that does not meet certain conservation value criteria (McLaughlin 2011). This requires a better understanding of the feedback loop between food and biodiversity, which will also be essential for meeting the SDG-2 (Zero Hunger) and the SDG-15 (Life on Land) (Ortiz et al. 2021), in addition to climate change which has strong linkages with both these goals. Furthermore, as demonstrated in a chapter by Sabbahi in this book, and by reference to Simmons et al. (2020), due to the critical ecosystem function and vital role of pollinators in guaranteeing food production and human well-being, conservation measures should cover not only species but also interspecies interactions, and careful management should be done in order to strengthen the essential links that exist within the ecosystem.

Another way is to reframe landscapes as social–ecological systems that allow for focusing on manageable components, or coexistence parameters through social, economic, or ecological approaches that are tailor made for each system (Crespin and Simonetti 2021). For example, transforming the food system from a biodiversity perspective implies the development of more biodiversity-supporting modes of food production. One way to do this is to retain pockets of habitat for wildlife within the agricultural landscape: some of which can be on farms; others can be patches of land 'spared for nature' within the wider farming landscape. The other way is to change farming methods to meet biodiversity conservation objectives (Benton et al. 2021).

Maintaining diversity within agricultural systems is not a novel approach, but a practice embraced by many smallholder farmers globally in many different ways. The nutritional and livelihood benefits of diverse food production systems are one way of achieving a sustainable food security. Such systems are also more resilient to environmental and climate risks or other shocks. In this regard, many studies, including some chapters in this book, have demonstrated the potential of forests as an important repository of food and other resources that can play a key role in fostering food security, especially if integrated into complex systems that are managed for multiple objectives and benefits (Sunderland 2011). This framework shifts the emphasis from focusing on production only to considering social–ecological dynamics, while enabling a comparison among landscapes. Moreover, examining the drivers and feedbacks facilitates the analysis of possible transitions between system states, e.g., from a lose–lose outcome to a more preferred one (Fischer et al. 2017).

4 The Transformative Change Framework

For decades, environmental and climate-related policies and interventions have generated an insufficient outcome in terms of sustainability and resilience in many parts of the world. The main reason behind this is the focus on treatment of symptoms without addressing the root causes. This is true for the climate action, which is still unable to trigger robust and transformative mitigation initiatives, or biodiversity-oriented actions which could not reverse the loss and extinction trends of many species. Virtually, all environmental and climate challenges have their causes in societal settings. Terrestrial biodiversity and habitat loss are driven by deforestation and land conversion for agricultural, urban, industrial, and transportation uses. Food production and habitat for the expanding human population are fundamental drivers. Oceans are stressed by overfishing and pollution from land and ship-based sources. Climate change is driven by fossil fuels for transportation, heating, and industry, and by intensive agriculture and deforestation (Uitto and Batra 2022).

Therefore, for transformative change to happen on the ground or be implemented, we need to identify the human-induced drivers or enablers of such change (*what needs to be done*), the pressures (*what needs to be eliminated*), the responses (*how it should be done*), and the challenges (*why it is not achieved*). As per the IPBES Global Assessment, incentives and capacity building, cross-sectoral cooperation, preemptive action, decision-making in the context of resilience and uncertainty, and environmental law and implementation are the five levers to spearhead transformative change (IPBES 2019). Figure 2 shows how transformative change can help achieve sustainability faster than business-as-usual (BAU) models, which often cross paths but are never synergized, thus taking different trajectories in a non-synchronized manner. The key enablers or drivers of change need to be identified first given their role in synergizing actions and policies that aligned with sustainability. This 'niche innovations' would also mean removing barriers and strengthening responses to be able to do so.

Examples of transformative change include, among others, the sustainable use and management of natural resources that combines actions to preserve and enhance biodiversity by increasing cultivated species and a higher likelihood of survival and augmentation of native species. This also includes improvements in landscape design

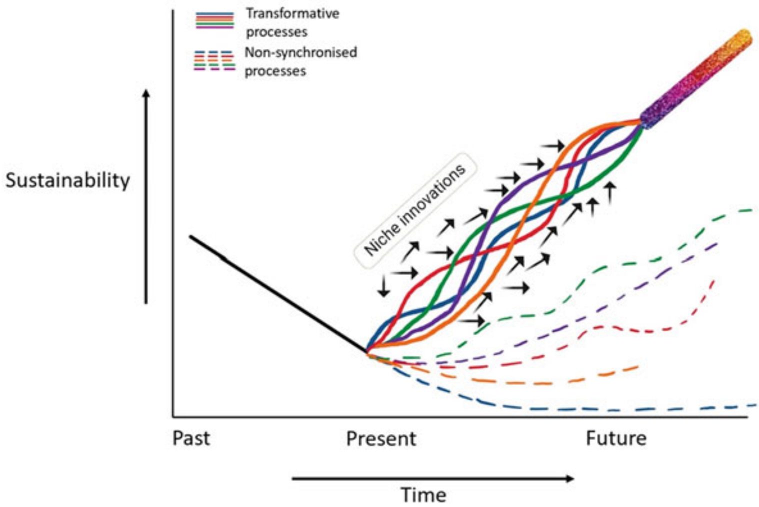


Fig. 2 Transformative processes versus non-synchronized processes. *Source* Nishi et al. (2021a)

and management, soil and water conservation, and other environmental qualities resulting in healthy landscapes and seascapes across multiple environmental services. Likewise, it includes enabling access to a diversity of resources for food, fuel, health, and other well-being requirements (Nishi et al. 2021b).

This section discusses the drivers or key enablers of transformative change in the context of food security, biodiversity and climate change nexus, the major pressures or feedback loop in this nexus, and the response options to tackle this nexus from a transformative lens.

4.1 Making Transformative Change a Pathway: Key Drivers/Enablers

As discussed above, climate change impacts food security and biodiversity both directly and indirectly through various dynamics, including those affecting ecosystem services and water resources. Many chapters published in this book provide an account of such impacts and their wider implications for both food security and biodiversity. Here, we outline the key enablers and drivers to tackle the nexus in a transformative way as gleaned from these chapters. This is in addition to what we mentioned earlier as options like land sharing and sparing to enhance both food security and biodiversity.

In this perspective, Delabre et al. (2021) claim that some initiatives, such as removing harmful incentives, promoting varied and sustainable diets, and strengthening sustainability standards, can be considered as key enablers (Fig. 3). However,

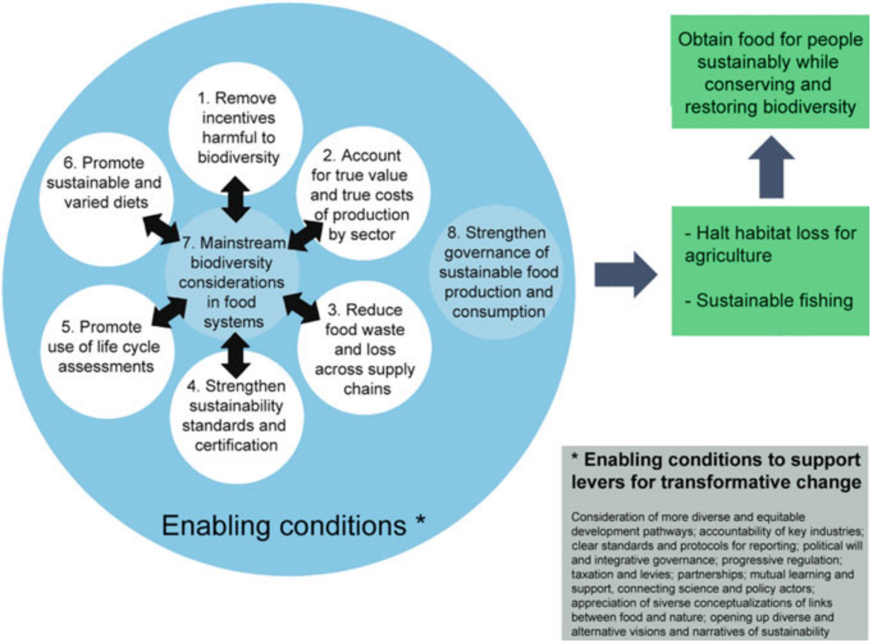


Fig. 3 Key actions and enabling conditions for transformative change. *Source* Delabre et al. (2021)

looking at the climate side of it, there is a need to also develop climate-resilient varieties, tackle the ocean acidification crisis, while also conserving biodiversity.

To instigate a transformative change process in the nexus area from a sustainability and resilience lens, developing more synergies between various sectors and stakeholders is among the enabling conditions. This may cover the following:

- **Synergizing biodiversity, climate, and farming-related activities**: Such synergies must focus, for instance, on the on-farm preservation of climate-resilient varieties that already exist in traditional and local crops. Those that are not resilient to the changing climate or pose a threat to future livelihoods must be further improved through cross-breeding to produce superior genotypes that will be resilient to increasing weather fluctuations, evolving pests, and increased resource scarcity (Bakala et al. 2020; Razzaq et al. 2021; Whitfield et al. 2021). Crop diversification is another method that can provide diversity of diet, improvement in income, and nutrition security, while being an efficient tool for mitigating the adverse effects of climate change (Mango et al. 2018; Ijaz et al. 2019). Synergizing must go beyond a mere mainstreaming of the biodiversity or climate concerns in existing agricultural policies or farming practices since this approach, in case it is inappropriately practiced, will not allow a transformative change toward sustainability and resilience. The reason is that farming systems remain shaped according to conventional models (i.e., unsustainable export-oriented intensive agriculture based mainly on monoculture farming, excessive agricultural chemical use, and overuse of water), while mainstreaming the biodiversity and climate concerns allows only for some incremental but marginal changes.

- **Merging traditional and modern knowledge**: The importance of traditional and ecological knowledge to modern society has grown, along with an increased recognition of its role in modern innovation, ecosystem restoration, and local livelihoods. Traditional and ecological knowledge should be increasingly considered as an 'indigenous science' for biodiversity conservation and climate adaptation because it is based on observation of natural processes, experimentation, and analysis; its prediction and forecasting capacity; and for being a system of management that has proven viable and efficient for thousands of years. In today's era, the gap between this 'indigenous science' and formal science, dominated by the Western vision, should be bridged and even eliminated. Coming up with a 'hybrid knowledge', where these two kinds of knowledge are integrated in inclusive and genuine ways according to local settings, seems a key enabling condition to fast-track transformative change.
- **The landscape approach**: In today's world, a wide variety of ecosystem services are declining at a faster speed, sometimes irreversibly, leaving societies climatically vulnerable and food insecure. This is one area which demands transformation as conventional methods to conserve or enhance these services do not seem impactful. This has mainly resulted due to the narrow focus of policies and their limited implementation scope, while the solution lies rather in the landscape approach. The latter helps identify workable pathways leading to ethical and legitimate outcomes for sustainable natural resource management (Nishi and Yamazaki 2020).
- **Sustainable management of natural resources and ecosystems**: There is no doubt that the protection of forests and wildlife has been an environmental priority for most developed and developing countries, while at the same time the deforestation remained a developmental need. This is another area that demands transformation through enhanced ecosystem restoration, implementation of nature-based solutions, ensuring high community engagement, protection and mainstreaming of traditional and local knowledge, maintenance of wild foods and local health baskets, and sustainable and climate-resilient development.
- **Protected area network**: There is a need for the expansion and connectivity of the protected areas with enhanced community engagement for their management. Besides, other effective area-based measures must be implemented to complement protected area networks, considering their role in supporting biodiversity, often outside protected areas (Takahashi et al. 2022).
- **Integrated action and multi-stakeholder engagement**: When handling a complex nexus that has scalar linkages, it becomes imperative to engage multiple actors and stakeholders with an approach that integrates various perspectives and is coherent across all governance levels (Nishi et al. 2021b). Examples include developing environment-friendly and value-added commodities from social–ecological systems and engaging 'intermediaries' who can facilitate collaboration between grassroots, government, and private actors (Takahashi et al. 2022).

- **Knowledge generation**: There is a growing need to establish resource centers and focus on developing mitigation technologies that are biodiversity friendly, while enhancing food security. Mitigation should also embrace ecological, economic, and cultural challenges.

4.2 Pressures and Hurdles in the Way of Transformative Change

Achieving transformative change toward a sustainable and resilient future in the context of the food security, biodiversity, and climate nexus requires the assessment and management of a range of constraints and challenges. This includes the following:

- **Barriers in community engagement**: In most developing countries, local communities that suffer the brunt of climatic changes are also producers of food and, in many cases, rely on biodiversity for livelihood. However, this may also risk biodiversity due to increased human–wildlife conflict, illegal logging, and unsustainable agricultural practices. All these result from awareness gaps and income opportunities.
- **Harmful incentives**: Modern agriculture that promotes monoculture farming has often been harmful for biodiversity as it competes for natural resources, especially land and water. In many cases, higher production is supplemented with chemical inputs (such synthetic pesticides and insecticides) which lead to the pollinator decline, which is itself a huge ecological and economic loss. In terms of climate, carbon forestry that was just mitigation oriented did not generate major benefits for biodiversity and was even harmful in many cases (Gupta and Dube 2018). Fundamentally, there is a need to open up discussions and possibilities for more sustainable and equitable economic models. This might include redefining GDP (Delabre et al. 2021) to make it inclusive and sustainability and resilience oriented, thus ensuring that development is fully connected to well-being and nature. Although these would constitute major measures, transformative change requires bold actions in this direction by diverse agents (Delabre et al. 2021).
- **Slow take-up of sustainable technologies**: Pacala and Socolow (2004) already wrote in *Science* that we possess technologies that could solve climate problem for the next half century. Sadly, the adoption of such technology has been too slow if compared with the pace of innovation and invention. Faster take-up of sustainable and climate-oriented technologies by the private sector under the incentivization by the public sector is necessary to remove this barrier.
- **Inequity**: This is one of the major barriers to transformation. Both inter-country/intra-country and inter-generational/intra-generational equity makes policy making and implementation a challenge. The capacities of each country to deal with environmental and climate issues being different, there is a need to bridge the gap in response mechanisms since the food security, biodiversity, and climate nexus-related challenges are almost global in nature.

- **Challenges associated with policy development, implementation, and coherence**: In a case study about Ethiopia for instance, Jiren et al. (2021) identified the policy incoherence—in terms of policy goals, instruments, and outputs—and incompatibilities of the nature of governing institutions with the complexity inherent within and between the sectors of food security and biodiversity conservation, as key challenges hampering the effectiveness of the governance of such sectors.

5 Prerequisites for an Efficient Transformative Change Process

Many crises related to the food-biodiversity-climate nexus require a sweeping transformative change process. If this goal can be reached, conventional BAU-driven solutions are not any more efficient. Regarding the climate crisis for instance, Engels (2022) claims that when it comes to overcoming it, many have placed their hopes in a technological vision of transformation. However, alternative solutions are needed. Certainly, there are no simple technological solutions that could achieve the urgently needed transformation fast enough, or in the required depth. The great societal transformation we have to achieve, to reach a better understanding of what is possible, will be difficult and complex, and we do not have any precedents to guide us. At its heart, it is a political problem, since it is always about questions like whose ways of life will increasingly come under pressure, who will be confronted with difficult impositions, how those sacrifices can be compensated for, and for whom climate protection will be facilitated. Therefore, the transformative change process should be inclusive and allow as many groups and levels of society as possible to experience co-benefits and develop ownership. This can happen when climate protection targets are aligned with a respective group's own interests and priorities. No matter whether it is citizens' energy cooperatives, climate-friendly business models, real-world laboratories, or efforts to strengthen municipal administrative bodies—all of these approaches are just as important as pursuing technological options.

The question of scale is also extremely important in a transformative change process. There is a need to focus on the pressures and hurdles, whose elimination will spearhead transformation at all scales, from global to local. Accordingly, actions taken toward the transformative change in the context of the nexus can be differentiated according to temporal scales. For instance, Uitto and Batra (2022) considers climate change impacts as something for the present not just for future. They are being felt now in many vulnerable settings in terms of changing climatic patterns and increased weather anomalies, storms, droughts, and wildfires. Irrespective of the success of mitigation actions, such impacts will continue to worsen for some time. Therefore, successful adaptation to climate change—reducing people's vulnerability and building the resilience of social–ecological systems—is an important priority where we must learn rapidly from experiences.

According to Batra et al. (2022), scaling-up is one mechanism for achieving transformational change and one indicator that transformational change is likely to be achieved. The authors define scaling-up as, for instance, an increase in the magnitude of global environmental benefits and/or expansion of geographical and sectoral areas covered by those benefits. Three factors emerged as important for ensuring long-term support for scaling-up processes: scaling-up becoming a political priority; gaining the support of political and economic influencers; and working through existing long-term structures that depend on the appropriate choice of partner institutions. Regarding the necessary conditions for enabling scaling-up, the authors focus on knowledge and information dissemination, participatory processes, and incentives and disincentives to motivate adoption of interventions; strong institutional and individual capacities, policy framework and operating guidelines, and sustainable financing for sustained implementation; and multi-stakeholder interactions and partnerships and systematic learning mechanisms, which allow the scaling-up process to be adaptable and cost effective in the face of changing contextual conditions. Concerning the mechanisms through which scaling-up can help achieve transformational change, the authors indicate replication, mainstreaming, linking, or catalytic effects:

- *Replication* refers to the implementation of the same intervention multiple times, thereby increasing the number of stakeholders and/or covering larger areas, by leveraging finance, knowledge, and policy.
- *Mainstreaming* involves the integration of an intervention's implementation within an institution's regular operations or simultaneously through multiple government sector agencies or other institutions (such as donors, civil society organizations, and the private sector), usually through a policy or legal framework. However, for mainstreaming to be efficient, it should be practiced, as mentioned above, in a way that deeply transforms policy-making processes not just making marginal changes.
- *Linking* involves the implementation of multiple types of interventions that, by design, all contribute to the same impact at the scale of a system (a landscape, seascape, ecoregion, a value chain, supply chain, or a national government) defined by environmental, economic, or administrative boundaries. Linking allows for addressing multiple areas in an integrated manner within a specific geographic or ecological unit.
- *Large-scale catalytic effects* are often associated with technological improvements whose benefits can be captured by harnessing, for instance, an effective market demand.

In addition to the above, there is the need to identify psychological, behavioral, social, cultural, economic, political, governance, institutional, demographic, technical, and technological factors that can be leveraged to achieve transformative change as a pathway to manage the nexus. In the same context, there is a need to explore how to address the underlying and direct causes of food insecurity, biodiversity loss, and climate change, by examining evidence of their increasing compounding and cascading effects, and social–ecological consequences.

For a transformative change to happen, we have to focus as well on those changes that can intentionally promote a sustainable and resilient future. This needs, among others, the assessment of the appropriate theories and frameworks for understanding deliberate transformative change, the consideration of different approaches to scaling transformative change, and the assessment of the normative, ethical, and political dimensions. In this regard, Uitto and Batra (2022) claim that many factors behind current environmental and climatic changes can usually be found in the spheres of policies and economic incentives that encourage unsustainable practices of production and consumption. Therefore, we need not only to address the direct drivers but also the indirect drivers of unsustainability. And we need high-level policy engagement to transform these systems. This may include the incorporation of the environmental and climate dimension and the coupled social–ecological systems, moving beyond individual projects to systems thinking and identifying unintended consequences.

Achieving transformative change entails as well the capacity to address a range of constraints and challenges that arise within and between political, legal, technological, physical, economic/financial, and other social systems, and the functioning of ecosystems, including challenges associated with policy development, implementation, and coherence; opposition arising from vested public and private interests facilitated by weak institutions; individual, social, and systemic inertia and lack of learning.

Accordingly, the actors' perceptions of the nexus challenges at all scales should be harmonized to ensure an optimal level of synergy in both policy goals and actions within the process. For instance, there is still a confusion between the impacts of individual and collective actions when it comes to the promotion of sustainability as a perspective of the transformative change process. The tension between what we can do individually and what needs to be structurally changed should be solved. There is even the risk of undervaluing the most important issues that we actually need to address, thus remaining in an incremental change process, which is important but insufficient to face the current urgency in addressing the current challenges driven by the nexus.

6 Conclusion

This chapter focuses on the food security, biodiversity, and climate change nexus and the transformative change as a pathway to manage related dynamics and challenges within the perspective of fostering both sustainability and resilience. To do so, we first analyzed the nexus to apprehend the various sub-interactions among its components. It was apparent then that climate change is a key driver of change in both biodiversity and food systems with the ability to cause both direct and indirect impacts. Meanwhile, it was established that food systems are also drivers of climate change, ecosystem degradation, and biodiversity loss. The latter, in turn, are among the factors of both food insecurity and increased global warming. These complex interlinkages clearly show that the efficient management of the nexus requires unconventional response mechanisms based on innovative approaches; transformative change being the most recommended one and the urgency to act in this direction is becoming a supported perspective worldwide.

Building on this, the analysis drew the contours of the transformative change framework and explored several ways through which such a change can be achieved in the context of food-biodiversity-climate nexus. Identifying the human-induced drivers or enablers of such change and the appropriate responses has been considered as a key part of the process. In the meantime, it was showed that the achievement of transformative change toward a sustainable and resilient future requires the assessment and management of a range of constraints and challenges.

Finally, the analysis identified a number of preconditions to ensure an efficient transformative change process in the context of the nexus. This encompasses the inclusiveness of the process, the question of scaling, the identification of different levers, the management of trade-offs, the prioritization of changes leading to sustainability and resilience, the harmonization of actors' perceptions of the nexus challenges, and the assessment of the normative, ethical, and political dimensions of the process.

References

Bakala HS, Singh G, Srivastava P (2020) Smart breeding for climate resilient agriculture. IntechOpen

Barrière O, Behnassi M, David G et al (eds) (2019) Coviability of social and ecological systems: reconnecting mankind to the biosphere in an era of global change: vol 1: the foundations of a new paradigm. Springer International Publishing, Cham

Batra G, Garcia J, Temnenko K (2022) Transformational change for achieving scale: lessons for a greener recovery. In: Uitto JI, Batra G (eds) Transformational change for people and the planet—evaluating environment and development. Springer, Cham, pp 27–38. http://doi.org/10.1007/978-3-030-78853-7

Benton TG, Bieg C, Harwatt H et al (2021) Food system impacts on biodiversity loss: three levers for food system transformation in support of nature

Berman S (2020, July 4) Crises only sometimes lead to change. Here's why. Foreign Policy. https://foreignpolicy.com/2020/07/04/coronavirus-crisis-turning-point-change/

Colman CB, Guerra A, Roque FDO et al (2022) Identifying priority regions and territorial planning strategies for conserving native vegetation in the Cerrado (Brazil) under different scenarios of land use changes. Sci Total Environ 807. https://doi.org/10.1016/j.scitotenv.2021.150998

Crespin SJ, Simonetti JA (2021) Traversing the food-biodiversity nexus towards coexistence by manipulating social–ecological system parameters. Conserv Lett 14:e12779. https://doi.org/10.1111/conl.12779

Daszak P, das Neves C, Amuasi J, Hayman D, Kuiken T, Roche B, Zambrana-Torrelio C, Buss P, Dundarova H, Feferholtz Y, Foldvari G, Igbinosa E, Junglen S, Liu Q, Suzan G, Uhart M, Wannous C, Woolaston K, Mosig Reidl P et al (2020) Workshop report on biodiversity and pandemics of the intergovernmental platform on biodiversity and ecosystem services. IPBES Secretariat. https://doi.org/10.5281/zenodo.4147317

Delabre I, Rodriguez LO, Smallwood JM et al (2021) Actions on sustainable food production and consumption for the post-2020 global biodiversity framework. Sci Adv. https://doi.org/10.1126/sciadv.abc8259
Dinesh D, Campbell B, Wollenberg L et al (2017) A step forward for agriculture at the UN climate talks. Koronivia Joint Work on Agriculture
Elver H, Oral N (2021) Food security, fisheries and ocean acidification: a human rights based approach. In: Research handbook on ocean acidification law and policy
Engels A (2022) Sociology for the climate. https://www.cliccs.uni-hamburg.de/about-cliccs/news/2022-news/2022-01-18-dkk-engels.html
FAO (2017) The future of food and agriculture: trends and challenges. Food and Agriculture Organization of the United Nations
Fischer J, Abson DJ, Bergsten A et al (2017) Reframing the food-biodiversity challenge. Trends Ecol Evol 32:335–345. https://doi.org/10.1016/j.tree.2017.02.009
Gattuso J-P, Mach KJ, Morgan G (2013) Ocean acidification and its impacts: an expert survey. Clim Change 117:725–738. https://doi.org/10.1007/s10584-012-0591-5
Global Environment Facility (GEF) (2020) White paper on a GEF COVID-19 response strategy: the complexities and imperatives of building back better. https://www.thegef.org/sites/default/files/council-meeting-documents/EN_GEF_C.59_Inf.14_White%20Paper%20on%20a%20GEF%20COVID-19%20Response%20Strategy_pdf
Godfray HCJ (2011) Food and biodiversity. Science 333:1231–1232. https://doi.org/10.1126/science.1211815
Gupta H, Dube LC (2018) Addressing biodiversity in climate change discourse: Paris mechanisms hold more promise. Int for Rev 20:104–114. https://doi.org/10.1505/146554818822824282
Gupta H, Dube LC (2021) Benefits of evaluating ecosystem services for implementation of nature-based solutions under the Paris agreement. In: Behnassi M, Gupta H, El Haiba M, Ramachandran G (eds) Social-Ecological Systems (SES): from risks and insecurity to viability and resilience. Springer International Publishing, Cham, pp 39–56
Gupta H, Nishi M, Gasparatos A (2021) Community-based responses for tackling environmental and socio-economic change and impacts in mountain social–ecological systems. Ambio. https://doi.org/10.1007/s13280-021-01651-6
Hasanzadeh Saray M, Baubekova A, Gohari A et al (2022) Optimization of water-energy-food nexus considering CO_2 emissions from cropland: a case study in northwest Iran. Appl Energy 307. https://doi.org/10.1016/j.apenergy.2021.118236
Ijaz M, Nawaz A, Ul-Allah S et al (2019) Crop diversification and food security. In: Hasanuzzaman M (ed) Agronomic crops: volume 1: production technologies. Springer, Singapore, pp 607–621
IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn, Germany
IPCC (2022) Climate change 2022: impacts, adaptation, and vulnerability. In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Contribution of Working Group II to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
Jiren TS, Leventon J, Jager NW et al (2021) Governance challenges at the interface of food security and biodiversity conservation: a multi-level case study from Ethiopia. Environ Manage 67:717–730. https://doi.org/10.1007/s00267-021-01432-7
Kebede AS, Nicholls RJ, Clarke D et al (2021) Integrated assessment of the food-water-land-ecosystems nexus in Europe: implications for sustainability. Sci Total Environ 768:144461. https://doi.org/10.1016/j.scitotenv.2020.144461
Khan SA, Kumar S, Hussain MZ, Kalra N (2009) Climate change, climate variability and Indian agriculture: impacts vulnerability and adaptation strategies. In: Singh SN (ed) Climate change and crops. Springer, Berlin

Liu S-K, Lin Z-E, Chiueh P-T (2022) Improving urban sustainability and resilience with the optimal arrangement of water-energy-food related practices. Sci Total Environ 812:152559. https://doi.org/10.1016/j.scitotenv.2021.152559

Mango N, Makate C, Mapemba L, Sopo M (2018) The role of crop diversification in improving household food security in central Malawi. Agric Food Secur 7:7. https://doi.org/10.1186/s40066-018-0160-x

McLaughlin DW (2011) Land, food, and biodiversity. Conserv Biol 25:1117–1120

Nishi M, Yamazaki M (2020) Landscape approaches for the post-2020 biodiversity agenda: perspectives from socio-ecological production landscapes and seascapes. Policy brief no 21

Nishi M, Subramanian SM, Gupta H et al (2021a) Introduction. In: Nishi M, Subramanian SM, Gupta H et al (eds) Fostering transformative change for sustainability in the context of Socio-Ecological Production Landscapes and Seascapes (SEPLS). Springer, Singapore, pp 1–16

Nishi M, Subramanian SM, Gupta H et al (2021b) Synthesis: conception, approaches and strategies for transformative change. In: Nishi M, Subramanian SM, Gupta H et al (eds) Fostering transformative change for sustainability in the context of Socio-Ecological Production Landscapes and Seascapes (SEPLS). Springer, Singapore, pp 229–249

O'Connell D, Abel N, Grigg N, Maru Y, Butler J, Cowie A, Stone-Jovicich S, Walker B, Wise R, Ruhweza A, Pearson L, Ryan P, Stafford Smith M (2016) Designing projects in a rapidly changing world: guidelines for embedding resilience, adaptation and transformation into sustainable development projects (Version 1.0). Scientific and Technical Advisory Panel, Global Environment Facility. https://www.stapgef.org/resources/advisory-documents/rapta-guidelines

Ogbolumani OA, Nwulu NI (2022) A food-energy-water nexus meta-model for food and energy security. Sustain Prod Consum 30:438–453. https://doi.org/10.1016/j.spc.2021.12.019

Ortiz AMD, Outhwaite CL, Dalin C, Newbold T (2021) A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. One Earth 4:88–101. https://doi.org/10.1016/j.oneear.2020.12.008

Pacala S, Socolow R (2004) Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305:968–972. https://doi.org/10.1126/science.1100103

Pörtner H-O, Scholes RJ, Agard J et al (2021) Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. Zenodo. https://zenodo.org/record/4659158

Ramirez-Contreras NE, Fontanilla-Díaz CA, Pardo LE et al (2022) Integral analysis of environmental and economic performance of combined agricultural intensification & bioenergy production in the Orinoquia region. J Environ Manage 303. https://doi.org/10.1016/j.jenvman.2021.114137

Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are insufficient to double global crop production by 2050. PLoS ONE 8:e66428. https://doi.org/10.1371/journal.pone.0066428

Razzaq A, Kaur P, Akhter N et al (2021) Next-generation breeding strategies for climate-ready crops. Front Plant Sci 12

Reuters (2010) Drought ruins Russia wheat, U.S. says no world crisis. Reuters

Rockström J, Steffen W, Noone K et al (2009) Planetary boundaries: exploring the safe operating space for humanity. Ecol Soc 14. https://doi.org/10.5751/ES-03180-140232

Simmons BI, Wauchope HS, Amano T et al (2020) Estimating the risk of species interaction loss in mutualistic communities. PLOS Biol 18:e3000843. https://doi.org/10.1371/journal.pbio.3000843

Stavi I, Paschalidou A, Kyriazopoulos AP et al (2021) Multidimensional food security nexus in drylands under the slow onset effects of climate change. Land 10:1350. https://doi.org/10.3390/land10121350

Sunderland TCH (2011) Food security: why is biodiversity important? Int For Rev 13(3)

Takahashi Y, Miwa K, Amaruzaman S et al (2022) Landscape approach for biodiversity, climate change and sustainable development co-benefits. In: ISAP 2021

Tscharntke T, Clough Y, Wanger TC et al (2012) Global food security, biodiversity conservation and the future of agricultural intensification. Biol Conserv 151:53–59. https://doi.org/10.1016/j.biocon.2012.01.068

Turley C, Gattuso J-P (2012) Future biological and ecosystem impacts of ocean acidification and their socioeconomic-policy implications. Curr Opin Environ Sustain 4:278–286. https://doi.org/10.1016/j.cosust.2012.05.007

Uitto JI, Batra G (2022) Transformational change for people and the planet: evaluating environment and development—introduction. In Uitto JI, Batra G (eds) Transformational change for people and the planet—evaluating environment and development. Springer, Cham, pp 1–13. https://doi.org/10.1007/978-3-030-78853-7

Whitfield S, Chapman S, Mahop MT et al (2021) Exploring assumptions in crop breeding for climate resilience: opportunities and principles for integrating climate model projections. Clim Change 164:38. https://doi.org/10.1007/s10584-021-02997-2

The Importance of Protected Areas in Mitigating Climate Change and Conserving Ecosystems in Latin America and the Caribbean

Cristián Bonacic, Constanza Arévalo, José Tomás Ibarra, and Jerry Laker

Abstract Biodiversity conservation in a world under climate change is a significant challenge for Latin America and the Caribbean (LAC), which holds 60% of global terrestrial life. Six of the ten most biodiverse countries (Brazil, Colombia, Ecuador, Mexico, Peru, and Venezuela) are in LAC, and biodiversity hotspots are well-represented along the region's coasts and mainland. The region has the most significant areas of tropical forest and large portions of subtropical forests, temperate steppe, and subantarctic Patagonia. Protected areas offer opportunities to conserve unique biodiversity, provide ecosystem services, and mitigate climate change effects. LAC's contribution to carbon capture, by protecting extensive forests and other natural ecosystems, is potentially opening tremendous economic opportunities under the green economy paradigm. This chapter describes the current status of protected areas in LAC and explains how this conservation mechanism should play a mitigation role. LAC's protected areas cover almost all types of terrestrial and marine ecosystems, and their number is increasing in the region. Although protected areas mitigate

C. Bonacic (✉) · C. Arévalo
Fauna Australis Conservation Laboratory, School of Agriculture and Forestry, Pontificia Universidad Católica de Chile, Santiago, Chile
e-mail: bona@uc.cl

C. Arévalo
e-mail: coarevalo@uc.cl

C. Bonacic
School of Veterinary Medicine and Center for Intercultural Research (CIIR), Pontificia Universidad Católica de Chile, Santiago, Chile

J. T. Ibarra
Fauna Australis Wildlife Conservation Research Laboratory, School of Agriculture and Forest Sciences and ECOS (Ecosystem-Complexity-Society) Co-Laboratory, Center for Local Development (CEDEL), Center for Intercultural and Indigenous Research (CIIR), Villarrica Campus, Pontificia Universidad Católica de Chile, Villarrica, Chile
e-mail: jtibarra@uc.cl

Cape Horn International Center for Global Change Studies and Biocultural Conservation (CHIC), Puerto Williams, Chile & Center of Applied Ecology and Sustainability (CAPES), Santiago, Chile

J. Laker
Kod Kod Field Research Station, La Araucanía, Chile

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_3

the effects of climate change on biodiversity, climate change and traditional environmental problems like deforestation, mining, and agriculture affect the viability of protected areas. Thus, their expansion and connectivity throughout the region are crucial to combat climate change and biodiversity loss. Nature is also essential to the region's biocultural diversity, including a miriad of complex cosmovisions and traditions. In LAC's unique ecosystems, rich biodiversity is spatially correlated with rich cultural diversity, granting opportunity for Indigenous Peoples and Local Communities to lead experiences in managing protected areas in biologically and culturally diverse ecosystems of LAC.

Keywords Biodiversity · Climate change · Conservation · Latin America · Protected areas · Sustainable development goals

1 Introduction

Latin America and the Caribbean (LAC) is one of the ecologically richest regions in the world, considering terrestrial and marine biodiversity, holding about 60% of the world's terrestrial life forms (UNEP-WCMC 2016). Latin America includes Mexico (the south of North America), central or Mesoamerica, and South America (total area: 20 million km^2) and comprises 13% of the world's land area. Latin America has the most significant portion of tropical rainforest and large quantities of subtropical forests, temperate steppe, and subantarctic Patagonia. Six out of the ten most biodiverse countries globally are found in Latin America (Brazil, Colombia, Ecuador, Mexico, Peru, and Venezuela). South America alone is the most biodiverse region on Earth, holding over 40% of the world's biodiversity and over 25% of the world's forests (Álvarez Malvido et al. 2021).

The distribution of protected areas in Latin America covers almost all terrestrial and marine ecosystems, from coral reef barriers in Mesoamerica to tundra-like ecosystems in Tierra del Fuego (Patagonia). Some countries have a more significant proportion of their lands covered by protected areas, and others have less. Still, the growing number of new protected areas has become a common trend throughout the region. Biodiversity hotspots are well-represented in Latin America along coasts and on the mainland. Over 10,000 marine and terrestrial protected areas throughout LAC protect over 8.8 million km^2 of land and water, which makes it the most protected region in the world, with 24.21% of the region's terrestrial surface area and 23.02% of its marine and coastal area under protection (UNEP-WCMC 2016). Over 60% of the region's protected areas are found in South America, comprising one-quarter of the region's terrestrial surface area and one-quarter of the region's marine and coastal surface area.

The LAC population was 662,157,288 in 2021, based on the United Nations' estimates (32 people per km^2). This is equivalent to about 8.42% of the total world population, making LAC the fourth most populated region in the world. A common feature of most Latin American countries is that people live in large metropolises, accounting for 82.5% of the total population. Massive movements of people from rural to urban areas occurred in the last 50 years, particularly during this century (Dufour and Piperata 2004). Latin America has cities with over 20 million people in Mexico and Brazil (Ciudad de Mexico and Sao Paulo), cities with close to 15 million inhabitants (Buenos Aires and Rio de Janeiro), and several with around ten million people (Lima and Bogota).[1] The three most significant populations are in Brazil (over 212 million people), Mexico (over 120 million people), and Colombia (around 50 million people). The vulnerability to climate change is high for large concentrations of people living in cities along the coastline, like Panama (Ciantelli et al. 2018), Rio de Janeiro, and Buenos Aires (Codignotto et al. 2012; Mascayano et al. 2021; Zambrano et al. 2017). Also, torrential rain, floods, and landslides are risk factors for large cities like Bogota and Quito (Lima Guamán et al. 2020), Sao Paulo, and Santiago of Chile (de Lima et al. 2018). Meanwhile, drought and glacier disappearance are a significant threat to human access to freshwater (Chevallier et al. 2011). The central Andes are the only tropical region of the world that depends on glacier melting for freshwater supply to large cities (Buxton et al. 2013). Quito in Ecuador, Lima in Perú, and La Paz in Bolivia are dependent on vanishing glaciers that are melting due to climate change (Buxton et al. 2013). Santiago of Chile is also a city that depends on glaciers for sustained water supply and has endured more than a decade of drought and more frequent heatwaves affecting over 7 million peoples' livelihoods (Borgias 2016; Palmeiro-Silva et al. 2020; Vicuña et al. 2018).

Another significant effect of climate change is the increased variability of harvest production. Rice, wheat, corn, beans, and soybeans play an essential role in Latin America due to their economic contributions and food security. According to Rodríguez De Luque et al. (2016), climate change affects how crops grow, adapt to higher temperatures, and less or more variable rainfall (i.e., off-season storms). Food security is an emerging concern in Latin America as the population grows and crop production levels off or declines in the region (Rodríguez De Luque et al. 2016).

This chapter describes the wealth of biodiversity and the importance of protected areas for climate change mitigation and adaptation in Latin America. We relate human population protection, access to a green economy, and more stability in a changing world if inclusive protected area coverage increases. Protected areas and nature conservation are included in the coming equation of sustainability, environmental justice, and economic growth. We emphasize why protected areas are a key element to achieve Sustainable Development Goals (SDGs). Finally, the cultural, ancestral, and non-economic values of sacred natural places and biodiversity are discussed. Living examples of conservation, community-based work for climate change mitigation, and biocultural heritage are presented as a proposition of a broader view of mitigation that embraces ecological, economic, and cultural challenges.

[1] Population by Country (2021)—Worldometer (worldometers.info).

2 Climate Change in Latin America

Latin America is particularly vulnerable to climate change, whose impacts are causing biodiversity loss, food insecurity, and economic problems (Fierros-González and López-Feldman 2021). The physical and geophysical impacts of climate change are expected to compound with one another, making their influence even more severe in the region, likely accentuating Latin America's vulnerabilities (Reyer et al. 2017). The most significant ocean warming is occurring in the southern hemisphere, increasing weather variability and the intensity of storm episodes, prolonged droughts, and the deterioration of border coastlines. Hurricanes have become more intense and frequent, threatening food security and increasing disease prevalence (Laffoley and Baxter 2016). Temperatures in 2020 were 1.0 °C, 0.8 °C, and 0.6 °C above the 1981–2010 average for Mesoamerica, the Caribbean, and South America, respectively (WMO 2021). Global warming is a concern when freshwater supplies are threatened by the rapid melting of glaciers in the Andes of western South America, impacting drinking water and irrigation water supply (NASA 2020). While larger glaciers in the southern Andes are predicted to melt at a slower pace, tropical glaciers are decreasing rapidly, and total melting is likely to occur under high warming levels (Reyer et al. 2017). Nonetheless, glaciers in the Chilean and Argentine Andes have been retreating during the last decades, with ice mass loss accelerating since 2010 (WMO 2021).

Key biodiversity hotspots are located along the Andes, with a large human population and agricultural activities. Frequent and more destructive hurricanes, torrential rains, prolonged droughts lasting more than a decade, dry lightning storms causing forest fires, and heatwaves have become common features in the region. On a global scale, the intensity of tropical cyclones is expected to increase by about 5%, and the proportion of higher intensity storms (categories 4 and 5) is expected to rise by 13% (Knutson et al. 2019). The role of coastal protected areas for mangrove forest conservation is becoming one of the most important arguments to foster protection in the Caribbean region. Countries like Cuba that protect coastal mangrove forests respond better to hurricanes than other countries where biodiversity and coastal areas have deteriorated, such as Haiti (Alscher 2011; López and Rodriguez 2018). Storms have been responsible for human displacement and land-use changes, adding pressure for natural areas to be converted into human settlements and agricultural land. Droughts are also widespread in the region, with many Latin American countries on the global list of the most water-stressed countries in the world (Hofste et al. 2019). Chile is the most vulnerable and highest-ranked Latin American country on the list, ranked 18th globally, and is currently facing a prolonged drought lasting over a decade. The Mediterranean Forest, located between 32° and 37° S latitude, is a unique 1000-km-long ecosystem along the western side of the Andes (Veblen et al. 2007), occurring between the driest desert in the world (the Atacama desert) and the temperate rainforest of southern Chile (Nadjar et al. 2007). Climate change is affecting this region with a decade of drought, causing the forest and shrublands to die out because of this prolonged condition. This ecoregion is a unique environment with high endemism. Many species of flora and fauna under threat by intensive agriculture are now experiencing added pressure from climate change acting on ecosystems and humans.

Similarly, unusually long dry periods affect the Amazon basin in Brazil and Mexico, with the 2020 drought in southern Amazon and the Pantanal being the worst in 60 years (WMO 2021). In the case of the Amazon basin, the ecosystem is believed to reach a tipping point when it reaches 40% deforestation, decreasing precipitation and shifting the regional climate to a warmer and drier one. The ecosystem would change from tropical rainforest to savanna (Sampaio et al. 2007). Irresponsible land-use change causing widespread deforestation, prolonged droughts, and heatwaves have aggravated the already fast decline of the native forest not only in the Amazon but also in the Paraguayan Chaco and the Pantanal region, one of the most extensive wetland ecosystems in the world and the most diverse in Latin America.

Amid the inevitable and detrimental impacts of climate change, protected areas can maintain biodiversity by minimizing these impacts. Climate change drives changes in wildlife distribution ranges. Also, habitat loss and degradation often impede migratory movements. Therefore, protected areas play an essential role in reducing the effects of climate change by providing wildlife with the space to adjust to rapidly changing climatic conditions (Lehikoinen et al. 2018). Increased protected area connectivity is crucial for the persistence of biodiversity as species' composition adapts to climate change, especially considering the expected severity of climate change impacts in Latin America. Strictly protected areas are common along country borders in Latin America. They are often clustered, creating high coverage and connectivity (Baldi et al. 2017; Thornton et al. 2020), making these regions particularly important for biodiversity conservation. Thornton et al. (2020) found clustering of protected areas near country borders in Argentina, Bolivia, Costa Rica, and Guatemala.

Deforestation rates within protected areas tend to be significantly lower (Leverington et al. 2010; Nagendra 2008). Tropical protected areas in the Americas, Africa, and Asia were found to have decreased carbon emissions by about 29% between 2000 and 2012 in comparison with expected rates of deforestation (Bebber and Butt 2017). However, recent data about Amazon deforestation is alarming. Ruiz-Vásquez et al. (2020) suggest that deforestation affects the climate in the entire region as atmospheric water evaporation is now altered as predicted 30 years ago (Shukla et al. 1990). The leading causes of deforestation remain the same, and the rate of deforestation is stable, bringing the Amazon to a tipping point of becoming a carbon emitter instead of the main carbon sink (Amigo 2020; Lovejoy and Nobre 2018). Cattle, road networks, human population growth, logging, and increased habitat replacement for crop production are the determinant variables of deforestation in the Amazon (de Andrade Vasconcelos et al. 2017). Forest loss in the Amazon affects the precipitation regime locally and elsewhere (Río de La Plata basin) in Argentina and Paraguay. One alternative solution to protect the Amazon Forest is the creation of new protected areas in the southern and southeastern basins where a semiarid forest acts as a barrier for further deforestation caused by climate change (Walker et al. 2009).

Beyond the Amazon and Río de La Plata basins, one of the largest rainforests of Latin America is now under threat in the Choco-Darién biodiversity hotspot—an area of more than 17 million square kilometers that is highly biodiverse. It includes 7500 species of plants (of which 1300 are endemic), 700 butterfly species, and more than 1500 bird species (Gomez et al. 2014). Its strategic location joins migration routes between north and south America and is one of the 25 most critical hotspots in the world. The Choco-Darien Global Ecoregion is the second-largest continuous rainforest in Latin America and includes southern Panama, the Colombia Andean region, and the north of Ecuador. Patterns of deforestation are closely related to agriculture, roads, and negatively correlated with country-level economic development. Wealthier areas are conserving/recovering more forest, and rural to urban migration releases pressure on deforestation (Fagua et al. 2019). Lastly, another critical and significant continuous rainforest of Latin America expands from the Yucatán peninsula in Mexico to Guatemala and Belize (known as the selva Maya). The tropical rainforest, which accounts for 14 million hectares, is home to the Maya culture and is the last remaining forest in the rich Mesoamerica biodiversity hotspot. As in the Choco-Darien and Amazon rainforest, deforestation and climate change affect these highly biodiverse ecosystems. Human pressure for opening the land to agriculture and roads, the tourism industry, and infrastructure are common threats for all of them.

Terrestrial protected areas worldwide store a large amount of carbon believed to be about 15% of the world's terrestrial carbon stock (Kapos et al. 2008). Out of all the regions in the world, LAC holds the second-largest amount of carbon in protected areas relative to the region's total carbon stock, with South America storing about a quarter of the entire region's carbon (Dudley et al. 2010). If we consider Central America and the Caribbean together, protected areas store 25.2% of the region's total carbon stock. The most significant and effective terrestrial carbon sequestration occurs in forests, including tropical forests seen throughout the Latin American region, particularly the Amazon rainforest, and temperate forests seen in Chile and Argentina. Almost three-quarters of the total area of humid tropical forest protected areas are in South America (Tabor et al. 2018); a region that is not only responsible for significant carbon sequestration but a high concentration of biodiversity. The Collaborative Partnership on Forests has long recognized the need to protect these forests by implementing protected areas, claiming that protected forest areas increase the resilience of ecosystems to climate change, protecting against climate change and adaptation through genetic resources and ecosystem services (CPF 2008).

While a case can be made for the importance of protected areas in mitigating the effects of climate change, the opposite is also true. Protected areas can be severely threatened by climate change, particularly when discussing marine protected areas worldwide. Well-managed marine protected areas can preserve marine ecosystems against the impacts of climate change and prevent acidification, decreased oxygen availability, sea-level rise, changes in species distribution, and the intensification of storms (Roberts et al. 2017). Nonetheless, due to ocean warming, acidification, and oxygen depletion, the habitats and species that marine protected areas are meant to protect will continue to be threatened, particularly in low-latitude and tropical regions (Bruno et al. 2018; García Molinos et al. 2015; Stuart-Smith et al. 2015), thus reducing the effectiveness of marine protected areas in mitigating the effects of climate change. The same applies to protected areas under the impact of climate change that are likely to see reduced effectiveness in safeguarding endangered habitats and biodiversity. Consequently, protected areas, both terrestrial and marine, will need to adapt to the ecological changes resulting from climate change. 42% of South American protected areas covering humid tropical forests are exposed to the highest novel climate risk, causing much uncertainty regarding the ability of species inhabiting the region to adapt to new climates and, therefore, to continue to be protected by these areas (Tabor et al. 2018). As a result, increasing connectivity among protected areas throughout the humid tropical forest region and other regions in Latin America is crucial to ensuring the continued protection of biodiversity as climate change shifts species distributions.

3 The Importance of Protected Areas in Latin America and Climate Change

Latin America spans multiple ecosystems, and its vulnerability to climate change is extremely high (Locatelli et al. 2011; Rodríguez De Luque et al. 2016). Local communities and scientific evidence suggest that climate change is changing the way of life, affecting food security, and decreasing biodiversity viability in multiple ecosystems (Iwama et al. 2021; Reyer et al. 2017). Climate change is causing sea-level rise, rising temperatures, land and forest degradation, salinization, loss of biodiversity, ocean acidification, desertification, and glacial retreat. Extreme weather events affect millions of people in cities and cause crop failure in vast regions of Latin America. Mainly, several million people live in the path of hurricanes and low-elevation coastal zones, rendering them vulnerable to sea-level rise, storm surges, and coastal flooding (Reyer et al. 2017).

In summary, the challenges coming from climate change affect human health, food production, and human settlement in unsafe areas, caused by coastal degradation, fisheries loss, biodiversity loss, and forest degradation, and contribute to global change. One example is the Amazon Forest, which is reaching a tipping point as deforestation increases its vulnerability to climate change. Hall (2011) stated the importance of protected areas to confront the diversity of challenges that climate change generates either in marine or terrestrial ecosystems of LAC. However, island sinking, coral reef decline, lower fishery production, and intense and more frequent forest fires compromise the viability and interconnection of protected areas in Latin America. Gámez et al. (2018) stated the importance of conserving protected areas and adapting to climate change by managing protected areas with local communities. The recovery of nature and closing the gap between people and nature have many advantages, from increasing quality of life to protecting biodiversity and capturing carbon. The latter is becoming an urgent need as climate change is causing ecological, economic, and social damage worldwide.

The concept of a "green economy" was introduced in the Conference of Sustainable Development Rio + 20 and refers to an economy that is low carbon, resource-efficient, and socially inclusive (UNGA 2012). A green economy under the sustainability paradigm results in improved human wellbeing and social equity, while significantly reducing environmental risks and ecological scarcities. The green economy adds to sustainability, the accountability of past environmental deterioration, the need to recover natural capital, and the need to produce economic and social benefits. In this perspective, protected areas are an investment for present and future generations. Restoration of deteriorated areas should be seen as an engine of green economy and development. Protected areas contribute to creating favorable ecological conditions that ensure the health and safety of surrounding human settlements amid the risks of climate change. For instance, protected areas throughout the LAC region, both public and private, hold important wild varieties of staple crops that could prove essential in combating the food security threats posed by climate change. These crop wild relatives may contribute beneficial genes to the region's staple crops, providing them with increased tolerance to rising temperature, salinity, and drought, as well as resistance to pests and diseases (Hunter et al. 2012). Protected areas can contribute to vital economic activities and help mitigate climate change local effects. Mainly, the stability of freshwater supply can be linked to forest and watershed conservation in many Andean regions of South America. The whole activity related to protected areas can be attributed to the green economy. Protected areas can impact the formation of an environmental culture around them, attracting investment for eco-related activities within and near such areas. Coupling biodiversity conservation through protected areas with climate change mitigation seems to be the logical solution in Latin America.

4 Latin American and Caribbean Protected Areas

Looking at the percentage of protected terrestrial and marine and coastal surface area throughout the entire LAC region (Table 1), it is apparent that the Caribbean subregion has the greatest relative coverage by far in comparison with Mesoamerica and South America. Nonetheless, the Caribbean region's terrestrial surface area is equivalent to about 1.3% of South America's and 9.5% of Mesoamerica's terrestrial surface area, while the subregion's marine and coastal surface area are equivalent to 27% of South America's and 70% of Mesoamerica's marine and coastal area. Consequently, the Caribbean region is quite successful in protecting its biodiversity and ecosystems, yet it is only a small portion of the entire LAC region. On the other hand, countries like Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Mexico, and Peru have significant protected area coverage (square kilometers of land and marine areas). But, relative to their total country size, protected areas only cover a fraction of these countries. For instance, while Mexico has the greatest coverage in

Mesoamerica in terms of square kilometers and number of protected areas (Fig. 1), every country in Mesoamerica, excluding El Salvador, protects a greater percentage of their country, although in terms of marine coverage, Mexico is in second place following Panama. In South America, there is a similar trend with countries like Brazil and Colombia, which have the greatest number of protected areas in the entire region by far (Fig. 1). Yet in terms of each country's total terrestrial and marine surface area, the greatest terrestrial protected area coverage occurs in Venezuela and French Guyana, while the greatest marine protected area coverage occurs in Chile, followed by Brazil. As a result, despite the high numbers of protected areas in South America and Mesoamerica and the great amount of protected square kilometers of land and sea, these regions have a significant portion of their total surface area left to be protected, particularly in Mesoamerica. Latin America has large countries compared to other regions of the world and has potential to increase protected area coverage to mitigate climate change and conserve biodiversity.

The Convention on Biological Diversity reported that between 2011 and 2020, the LAC region made significant improvements toward meeting Aichi Biodiversity Target 11, which focuses on increasing and improving protected areas (UNEP-WCMC 2016). Specifically, they state that "the region has developed an extensive protected area network, consisting of state and community and private reserves. This protected area network is also increasing in effectiveness in many countries in the region."

5 Traditional Knowledge, Climate Change, and Protected Areas

Traditional and Local Knowledge (TLK) must play a role in the management of protected areas, mainly when climate change rapidly affects local communities and puts their livelihoods under threat. Local communities have long noticed that their environment is rapidly changing and are aware of climate change. Their historical knowledge of local ecosystems and their cycles and variability make them key agents for ecosystem management. Their accumulated knowledge across generations, as part of collective practices in the environment, provides unique insights into the current challenges regarding biodiversity conservation and ecosystem functioning (Anbleyth-Evans and Lacy 2019; Reyer et al. 2017). Therefore, the role of TLK in biodiversity conservation cannot be underestimated.

Moreover, large spans of native rainforests are owned by traditional local societies. Their fate is closely tied to forest conservation. Current threats like mining, forest burning for livestock rearing and grain production for livestock feed, oil exploration, and road construction are among the main drivers of biodiversity extinction and habitat loss in Latin America. Climate change is increasing ecosystem vulnerability to human actions, and nature under local communities' protection should be seen as a buffer to mitigate the effects of climate change. Examples of this are: oil exploration

Table 1 Latin America and Caribbean protected area data

Country	Terrestrial surface area (km^2)	Marine and coastal area (km^2)	Number of protected areas	Terrestrial protected area coverage (km^2)	Percent terrestrial protected area coverage (%)	Marine protected area coverage (km^2)	Percent marine protected area coverage (%)	Region
Anguilla	86	92,654	7	10	11.14	63	0.07	Caribbean
Antigua and Barbuda	455	108,492	18	96	21.00	325	0.30	Caribbean
Argentina	2,785,328	1,083,151	463	236,109	8.48	127,449	11.77	South America
Aruba	189	25,214	3	36	18.92	0	0.00	Caribbean
Bahamas	13,458	597,705	54	4930	36.63	47,355	7.92	Caribbean
Barbados	444	185,020	9	6	1.27	10	0.01	Caribbean
Belize	22,298	36,250	120	8372	37.55	3994	11.02	Mesoamerica
Bermuda	72	451,644	28	2	2.08	0	0.00	Caribbean
Bolivia	1,089,909	0	167	336,407	30.87	0	0.00	South America
Brazil	8,529,399	3,672,584	3202	2,584,808	30.30	985,042	26.82	South America
The British Virgin Islands	176	80,529	88	16	9.11	3	0.00	Caribbean
Cayman Islands	289	119,605	58	31	10.76	93	0.08	Caribbean
Chile	759,821	3,657,313	222	158,788	20.90	1,511,390	41.33	South America
Colombia	1,145,033	730,742	1341	193,618	16.91	125,437	17.17	South America
Costa Rica	51,636	576,110	165	14,673	28.42	15,721	2.73	Mesoamerica
Cuba	111,643	365,756	230	18,119	16.23	14,090	3.85	Caribbean
Curacao	451	30,535	14	71	15.75	12	0.04	Caribbean
Dominica	766	28,749	9	168	21.96	10	0.03	Caribbean

(continued)

Table 1 (continued)

Country	Terrestrial surface area (km^2)	Marine and coastal area (km^2)	Number of protected areas	Terrestrial protected area coverage (km^2)	Percent terrestrial protected area coverage (%)	Marine protected area coverage (km^2)	Percent marine protected area coverage (%)	Region
Dominican Republic	48,510	270,774	147	12,727	26.24	48,625	17.96	Caribbean
Dutch Caribbean	323	25,112	14	92	28.37	25,112	100.00	Caribbean
Ecuador	258,139	1,079,901	83	59,932	23.22	144,123	13.35	South America
El Salvador	20,573	94,238	202	1778	8.64	666	0.71	Mesoamerica
Falkland Islands	12,401	549,092	33	61	0.49	52	0.01	South America
French Guyana	83,035	136,564	39	43,588	52.49	1365	1.00	South America
Grenada	374	26,282	49	36	9.54	26	0.10	Caribbean
Guadeloupe	1679	91,039	87	1172	69.82	90,959	99.91	Caribbean
Guatemala	109,922	118,336	352	22,116	20.12	954	0.81	Mesoamerica
Guyana	211,200	136,910	5	17,953	8.50	26	0.02	South America
Haiti	27,390	123,867	27	2357	8.61	1826	1.47	Caribbean
Honduras	113,291	219,971	118	26,568	23.45	10,070	4.58	Mesoamerica
Jamaica	11,059	246,488	154	1789	16.18	1860	0.75	Caribbean
Martinique	1150	47,644	73	926	80.53	47,904	100.00	Caribbean
Mexico	1,965,285	3,284,660	1146	284,801	14.49	707,956	21.55	Mesoamerica
Montserrat	101	7628	1	11	11.11	0	0.00	Caribbean
Nicaragua	129,222	223,935	84	27,585	21.35	7597	3.39	Mesoamerica
Panamá	75,498	332,643	114	23,682	31.37	89,297	26.84	Mesoamerica

(continued)

Table 1 (continued)

Country	Terrestrial surface area (km^2)	Marine and coastal area (km^2)	Number of protected areas	Terrestrial protected area coverage (km^2)	Percent terrestrial protected area coverage (%)	Marine protected area coverage (km^2)	Percent marine protected area coverage (%)	Region
Paraguay	401,498	0	98	57,473	14.31	0	0.00	South America
Peru	1,298,537	838,330	264	289,155	22.27	4037	0.48	South America
Puerto Rico	9041	176,163	109	667	7.38	3201	1.82	Caribbean
Saint Barthélemy	25	4318	5	5	20.36	4244	98.29	Caribbean
Sint Maarten	36	498	3	0	0.73	43	8.70	Caribbean
St. Kitts and Nevis	271	10,263	10	62	22.90	408	3.98	Caribbean
St. Lucia	622	15,560	42	117	18.75	34	0.22	Caribbean
St. Martin	60	1069	22	8	12.77	1031	96.43	Caribbean
St. Vincent and the Grenadines	410	36,511	55	92	22.42	80	0.22	Caribbean
Suriname	147,558	128,363	22	21,426	14.52	1981	1.54	South America
Trinidad and Tobago	5213	75,798	44	1595	30.59	37	0.05	Caribbean
Turks and Caicos Islands	1018	154,242	34	452	44.37	150	0.10	Caribbean
U.S. Virgin Islands	376	36,030	46	54	14.37	307	0.85	Caribbean
Uruguay	178,460	130,098	22	6557	3.67	979	0.75	South America
Venezuela	917,368	473,325	290	521,790	56.88	20,590	4.35	South America

Source Data obtained from Protected Planet (protectedplanet.net)

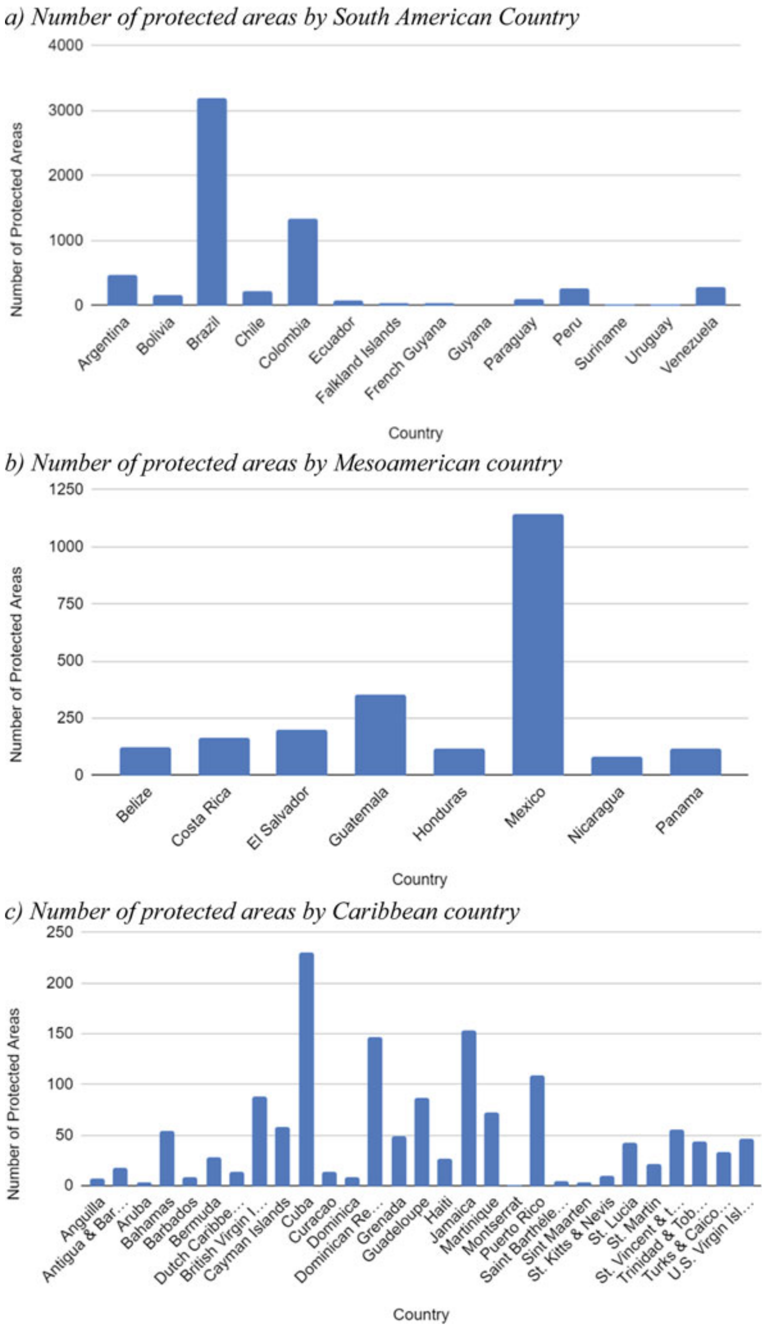


Fig. 1 Number of protected areas (terrestrial and marine) per country in **a** South America, **b** Mesoamerica, and **c** the Caribbean. *Source* Graphs created using data from Protected Planet (protectedplanet.net)

in Ecuador (Finer et al. 2008); slash and burn deforestation in the Cerrado of Brazil for soybean plantations (Pivello 2011); forest burning for livestock production in the Amazon (França et al. 2021); road construction in Choco-Darien between Colombia and Panama (Gómez et al. 2014); tourism development in the Yucatan peninsula mangrove forests (Mexico Daily Post 2021); and habitat replacement for agriculture in El Chaco of Paraguay (Cardozo et al. 2013).

Local people conserving large areas of biologically and culturally rich countries offer accumulated experiences and an opportunity for biodiversity conservation and climate action. LAC represents a unique set of ecosystems where rich biodiversity is spatially correlated with rich cultural diversity. Multiple examples of local indigenous peoples preserving nature are widespread in LAC. For example, the Mosquitia Biosphere reserve in Honduras, the Maya jungle in Guatemala and Mexico, and the rich cultural diversity of the Amazon people.

Latin America was the cradle of three main civilizations that developed agriculture, technologies, and culture intertwined with biodiversity knowledge. Mayan people have inhabited Mesoamerica for the last three thousand years, suggesting that Mayan farmers have successfully adapted to maintain both nature and culture in the long run (Barrera-Bassols and Toledo 2005; Herrera Lima and Gómez 2017). Jaguars, snakes, and other species of animals and plants played a crucial role in their cosmovision. Knowledge of flora and fauna shows a deep understanding of animal-plant relationships and zoological behavior, ethnobotany, and nature's importance for agriculture. Multiple indigenous groups throughout Latin America remain uncontacted by the outside world, living in resource-rich environments that these groups manage. However, attempts by the outside world to make contact with uncontacted tribes to gain access to these resources put these indigenous groups in grave danger, along with the environments they manage and conserve. In 2015, a national park was created on the Peruvian side of the Sierra del Divisor region to protect uncontacted tribes and their unique environment, including rare and endangered animal species. Nonetheless, like many other protected areas throughout the region, the lack of proper park management has meant that illegal loggers and miners, as well as drug traffickers, continue to be present in the area (Survival International 2021).

LAC offers unique opportunities to confront the immediate impact of climate change. Its large size, rich biodiversity, pristine and still well-preserved ecosystems, and the existence of large portions of land owned by local communities should be regarded as an opportunity for effective climate change mitigation. Implementing the proper mechanisms for the conservation of forests and other significant natural ecosystems should be considered a priority for effective climate change prevention and mitigation, carbon sequestration, and ecosystem functioning processes for the benefit of society. It is essential to combine economic and environmental legislation to utilize the vast potential of nature conservation for climate change action and sustainable development as habitat loss and ecological degradation rapidly increase, aggravated by climate change phenomena like extreme episodes of rain, drought, hurricanes, tornadoes, and forest fires. It is urgent to develop a regional strategy that secures nature, mitigates climate change, and provides ecosystem services for the sustainability of local livelihoods.

6 Concluding Remarks

Two of the most, if not the most, significant environmental issues faced by our world are biodiversity loss and climate change, with extensive scientific evidence indicating that we are currently living through a sixth mass extinction. The LAC region holds about 60% of the planet's terrestrial life forms, and six out of the ten most biodiverse countries in the world are located in the region. Thus, protected areas play a crucial role throughout LAC, serving as an essential tool to combat the effects of climate change and to reduce biodiversity loss. Some of the climate change effects already impacting the region include increased storm events and storm intensity, drought, forest fires, biodiversity loss, threatened water supplies, and threatened food security, among many others. The effects of climate change are expected to accentuate the region's vulnerabilities, making the LAC region particularly susceptible to climate change.

Protected areas mitigate the effects of climate change on biodiversity by providing wildlife with space to adjust to changing climatic conditions. Terrestrial protected areas throughout the LAC region provide important vegetative genetic diversity, which may prove essential in fighting food insecurity caused by climate change. Additionally, these areas store large amounts of carbon, particularly those protecting the Amazon rainforest and temperate forests in the southern part of the region, and serve an essential role in combating deforestation within these crucial ecosystems. For protected areas to effectively fight the effects of climate change in the LAC region, the coverage of terrestrial and marine/coastal protected areas must be extended to cover a more significant proportion of natural ecosystems, particularly areas considered as biodiversity hotspots. Furthermore, increased protected area connectivity is essential for the persistence of biodiversity as climate change shifts the distribution of species. It is also imperative to consider the essential historical knowledge of ecosystems held by local and indigenous communities, whose fate is often linked to the protection of such ecosystems. The incorporation of traditional knowledge is an essential piece to consider in the management of protected areas. Indigenous Peoples and Local Communities should play a role in managing the protected areas created to protect the ecosystems they have long inhabited.

Acknowledgements We thank The Sustainable Development Goals Observatory from Universidad de los Andes (project ODS 2 and 15 led by Prof. Bonacic). We also thank ANID/Fondecyt Regular 1200291 and 1221644, and the Center for Intercultural and Indigenous Research—CIIR (ANID/FONDAP/15110006). We acknowledge the support of the project for Technological Centers of Excellence with Basal Financing ANID-Chile to the Cape Horn International Center (CHIC-ANID PIA/BASAL PFB210018) and the Center of Applied Ecology and Sustainability—CAPES (ANID PIA/BASAL FB0002).

References

Alscher S (2011) Environmental degradation and migration on Hispaniola Island. Int Migr 49(Suppl. 1). http://doi.org/10.1111/j.1468-2435.2010.00664.x

Álvarez Malvido M, Lázaro C, De Lamo X, Juffe-Bignoli D, Cao R, Bueno P, Sofrony C, Maretti C, Guerra F (eds) (2021) Latin America and the Caribbean protected planet report 2020. Red-Parques, UNEP-WCMC, WCPA-IUCN, WWF, CONANP and IAPA Project, Mexico City, Mexico; Cambridge, UK; Gland, Switzerland; Bogota, Colombia

Amigo I (2020) When will the Amazon hit a tipping point? Nature 578(7796):505–507. https://doi.org/10.1038/d41586-020-00508-4

Anbleyth-Evans J, Lacy SN (2019) Feedback between fisher local ecological knowledge and scientific epistemologies in England: building bridges for biodiversity conservation. Marit Stud 18(2):189–203. http://doi.org/10.1007/S40152-019-00136-3

Baldi G, Texeira M, Martin OA, Grau R, Jobbágy EG (2017) Opportunities drive the global distribution of protected areas. PeerJ 5:e2989

Barrera-Bassols N, Toledo VM (2005) Ethnoecology of the Yucatec Maya: symbolism, knowledge and management of natural resources. J Latin Am Geogr 4(1):9–41. https://doi.org/10.1353/lag.2005.0021

Bebber DP, Butt N (2017) Tropical protected areas reduced deforestation carbon emissions by one third from 2000–2012. Sci Rep 7(1). http://doi.org/10.1038/s41598-017-14467-w

Borgias S (2016) Law, scarcity, and social movements: water governance in Chile's Maipo River Basin. ProQuest dissertations and theses

Bruno JF, Bates AE, Cacciapaglia C et al (2018) Climate change threatens the world's marine protected areas. Nature Clim Change 8:499–503. https://doi.org/10.1038/s41558-018-0149-2

Buxton N, Escobar M, Purkey D, Lima N (2013) Water scarcity, climate change and Bolivia: planning for climate uncertainties. Stockholm Environment Institute

Cardozo R, Palacios F, Caballero J, Rodas O (2013) Monitoreo de cambio de uso del suelo en el Gran Chaco Americano. XVI Simpósio Brasileiro de Sensoriamento Remoto, 2004

Chevallier P, Pouyaud B, Suarez W, Condom T (2011) Climate change threats to environment in the tropical Andes: glaciers and water resources. Reg Environ Change 11(Suppl. 1). http://doi.org/10.1007/s10113-010-0177-6

Ciantelli C, Palazzi E, Von Hardenberg J, Vaccaro C, Tittarelli F, Bonazza A (2018) How can climate change affect the UNESCO cultural heritage sites in panama? Geosciences (Switzerland) 8(8). http://doi.org/10.3390/geosciences8080296

Codignotto JO, Dragani WC, Martin PB, Simionato CG, Medina RA, Alonso G (2012) Wind-wave climate change and increasing erosion in the outer Río de la Plata, Argentina. Cont Shelf Res 38. https://doi.org/10.1016/j.csr.2012.03.013

CPF (2008) Strategic framework for forests and climate change: a proposal by the collaborative partnership on forests for a coordinated forest-sector response to climate change

de Andrade Vasconcelos PG, Angelo H, de Almeida AN, Matricardi EA, Miguel EP, de Paula MF, Goncalez JC, Joaquim MS (2017) Determinants of the Brazilian Amazon deforestation. Afr J Agric Res 12(3). http://doi.org/10.5897/ajar2016.11966

de Lima GN, Lombardo MA, Magaña V (2018) Urban water supply and the changes in the precipitation patterns in the metropolitan area of São Paulo, Brazil. Appl Geogr 94. https://doi.org/10.1016/j.apgeog.2018.03.010

Dudley N, Stolton S, Belokurov A, Krueger L, Lopoukhine N, MacKinnon K, Sandwith T, Sekhran N (2010) Natural solutions: protected areas helping people cope with climate change. IUCNWCPA, TNC, UNDP, WCS, The World Bank and WWF, Gland, Switzerland; Washington, DC, USA; New York, NY, USA; Available online: https://www.iucn.org/downloads/natural_solutions.pdf

Dufour DL, Piperata BA (2004) Rural-to-urban migration in Latin America: an update and thoughts on the model. Am J Hum Biol 16(4):395–404. https://doi.org/10.1002/AJHB.20043

Fagua JC, Baggio JA, Ramsey RD (2019) Drivers of forest cover changes in the Chocó-Darien global ecoregion of South America. Ecosphere 10(3):e02648. https://doi.org/10.1002/ecs2.2648

Fierros-González I, López-Feldman A (2021) Farmers' perception of climate change: a review of the literature for Latin America. Front Environ Sci 9. http://doi.org/10.3389/fenvs.2021.672399
Finer M, Jenkins CN, Pimm SL, Keane B, Ross C (2008) Oil and gas projects in the Western Amazon: threats to wilderness, biodiversity, and indigenous peoples. PLoS ONE 3(8). http://doi.org/10.1371/journal.pone.0002932
França F, Solar R, Lees AC, Martins LP, Berenguer E, Barlow J (2021) Reassessing the role of cattle and pasture in Brazil's deforestation: a response to "fire, deforestation, and livestock: when the smoke clears." Land Use Policy 108. http://doi.org/10.1016/j.landusepol.2020.105195
Gámez AE, Ivanova A, Juárez E (2018) Community adaptation to climate change and biodiversity conservation in natural protected areas: the case of El Vizcaíno Biosphere Reserve, Mexico. In: Mexican natural resources management and biodiversity conservation: recent case studies. http://doi.org/10.1007/978-3-319-90584-6_18
García Molinos J et al (2015) Climate velocity and the future global redistribution of marine biodiversity. Nat Clim Change 6:83–88
Gomez L, Naranjo L, García C, Dereix C (2014) Chocó-Darién landscape management in priority watersheds
Gómez L, Suárez C, Trujillo A, Bravo AM, Rojas V, Hernandez N, Vargas MC (2014) Landscape management in Chocó-Darién priority watersheds. In: WWF-Colombia, Bogotá, Colombia
Hall A (2011) Getting REDD-y: conservation and climate change in Latin America. Latin Am Res Rev 46. https://doi.org/10.1353/lar.2011.0039
Herrera Lima S, Gómez MV (2017) The show of nature and culture: "Los Mayas" in the Quintana Roo Museums. Mitologías Hoy 16. https://doi.org/10.5565/rev/mitologias.487
Hofste RW, Reig P, Schleifer L (2019) 17 countries, home to one-quarter of the world's population, face extremely high water stress. World Resources Institute. https://www.wri.org/insights/17-countries-home-one-quarter-worlds-population-face-extremely-high-water-stress
Hunter D, Maxted N, Heywood V, Kell S, Borelli T (2012) Protected areas and the challenge of conserving crop wild relatives. Parks 18(1). http://doi.org/10.2305/IUCN.CH
Iwama AY, Araos F, Anbleyth-Evans J, Marchezini V, Ruiz-Luna A, Ther-Ríos F, Bacigalupe G, Perkins PE (2021) Multiple knowledge systems and participatory actions in slow-onset effects of climate change: insights and perspectives in Latin America and the Caribbean. Curr Opin Environ Sustain 50. http://doi.org/10.1016/j.cosust.2021.01.010
Kapos V, Bavilious C, Campbell A, Dickson B, Gibbs H, Hansen M, Lysenko I, Miles L, Price J, Scharlemann JPW, Trumper K (2008) Carbon and biodiversity: a demonstration atlas. United Nations Environment Programme, World Conservation Monitoring Centre, Cambridge, UK, 197 p
Knutson T, Camargo SJ, Chan JC, Emanuel K, Ho CH, Kossin J, Mohapatra M, Satoh M, Sugi M, Walsh K et al (2019) Tropical cyclones and climate change assessment: part II. Projected response to anthropogenic warming. Bull Am Meteorol Soc 101(3):E303–E322
Laffoley D, Baxter JM (eds) (2016) Explaining ocean warming: causes, scale, effects and consequences. Full report. IUCN, Gland, Switzerland, 456 p. Individual chapters within this report should be referenced as: Author(s) (2016) Title of chapter. In: Laffoley D, Baxter JM (eds) Explaining ocean warming: causes, scale, effects and consequences. Full report. IUCN, Gland, Switzerland
Lehikoinen P, Santangeli A, Jaatinen K, Rajasärkkä A, Lehikoinen A (2018) Protected areas act as a buffer against detrimental effects of climate change—evidence from large-scale, long-term abundance data. Glob Change Biol 25:304–313. https://doi.org/10.1111/gcb.14461
Leverington F, Costa KL, Pavese H, Lisle A, Hockings M (2010) A global analysis of protected area management effectiveness. Environ Manage 46:685–698
Lima Guamán PR, Santamaría Carrera JL, Flor M (2020) Changes in rainfall patterns on the upper Ecuadorian Andean mountains: analysis of extreme precipitation, ENSO effects and shifts of annual rainfall variation. ACI Avances En Ciencias e Ingenierías 11(3). http://doi.org/10.18272/aci.v11i3.1067

Locatelli B, Evans V, Wardell A, Andrade A, Vignola R (2011) Forests and climate change in Latin America: linking adaptation and mitigation. Forests 2(1):431–450. http://doi.org/10.3390/F2010431

López J, Rodriguez G (2018) Actions aimed at reducing the vulnerability of a mangrove sector south of the province of Artemisa, Cuba. Revista Cubana de Ciencias Forestales 6(2)

Lovejoy TE, Nobre C (2018) Amazon tipping point. Sci Adv 4(2). http://doi.org/10.1126/sciadv.aat2340

Mascayano F, Alvarado R, Martínez-Viciana C, Irarázaval M, Durand-Arias S, Freytes M, Montenegro C, Susser E, Bruni A (2021) 30 years from the Caracas declaration: the situation of psychiatric hospitals in Latin America and the Caribbean prior, during and after the COVID-19 pandemic. Soc Psychiatry Psychiatr Epidemiol 2021(1):1–3. https://doi.org/10.1007/S00127-021-02100-1

Mexico Daily Post (2021) Efforts are underway to protect and restore mangrove forests in the Yucatan. https://mexicodailypost.com/2021/11/07/efforts-are-underway-to-protect-and-restore-mangrove-forests/

Nadjar R, Gutiérrez A, Kissling W, Armesto J, Huth A (2007) Ecological impacts of different harvesting scenarios for temperate evergreen rain forest in southern Chile—a simulation experiment. For Ecol Manag 252(1–3)

Nagendra H (2008) Do parks work? Impact of protected areas on land cover clearing. Ambio 37(5). http://doi.org/10.1579/06-R-184.1

NASA (2020) In: Greicius T (ed) Ice melt linked to accelerated regional freshwater depletion. NASA. https://www.nasa.gov/feature/jpl/ice-melt-linked-to-accelerated-regional-freshwater-depletion

Palmeiro-Silva YK, Cifuentes LA, Cortés S, Olivares M, Silva I (2020) The threat of climate change on population health and the urgent need to act. Revista Medica de Chile 148(11). http://doi.org/10.4067/S0034-98872020001101652

Pivello VR (2011) The use of fire in the Cerrado and Amazonian rainforests of Brazil: past and present. Fire Ecol 7(1). http://doi.org/10.4996/fireecology.0701024

Reyer CPO, Adams S, Albrecht T, Baarsch F, Boit A, Canales Trujillo N, Cartsburg M, Coumou D, Eden A, Fernandes E, Langerwisch F, Marcus R, Mengel M, Mira-Salama D, Perette M, Pereznieto P, Rammig A, Reinhardt J, Robinson A et al (2017) Climate change impacts in Latin America and the Caribbean and their implications for development. Reg Environ Change 17(6):1601–1621. https://doi.org/10.1007/S10113-015-0854-6

Roberts CM, O'Leary BC, Mccauley DJ, Cury PM, Duarte CM, Lubchenco J, Pauly D, Sáenz-Arroyo A, Sumaila UR, Wilson RW, Worm B, Castilla JC (2017) Marine reserves can mitigate and promote adaptation to climate change. Proc Nat Acad Sci U S A 114(24). http://doi.org/10.1073/pnas.1701262114

Rodríguez De Luque JJ, González Rodríguez CE, Gourdji S, Mason-D'croz D, Obando-Bonilla D, Mesa-Diez J, Prager SD (2016) Socio-economic impacts of climate change in Latin America and the Caribbean: 2020–2045. Cuadernos de Desarrollo Rural 13(78). http://doi.org/10.11144/Javeriana.cdr13-78.iscc

Ruiz-Vásquez M, Arias PA, Martínez JA, Espinoza JC (2020) Effects of Amazon basin deforestation on regional atmospheric circulation and water vapor transport towards tropical South America. Clim Dyn 54(9–10). http://doi.org/10.1007/s00382-020-05223-4

Sampaio G, Nobre C, Costa MH, Satyamurty P, Soares-Filho BS, Cardoso M (2007) Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. Geophys Res Lett 34:L17709. https://doi.org/10.1029/2007GL030612

Shukla J, Nobre C, Sellers P (1990) Amazon deforestation and climate change. Science 247(4948). http://doi.org/10.1126/science.247.4948.1322

Stuart-Smith RD, Edgar GJ, Barrett NS, Kininmonth SJ, Bates AE (2015) Thermal biases and vulnerability to warming in the world's marine fauna. Nature 528:88–92

Survival International (2021) The uncontacted frontier. https://www.survivalinternational.org/tribes/amazonuncontactedfrontier

Tabor K, Hewson J, Tien H, González-Roglich M, Hole D, Williams JW (2018) Tropical protected areas under increasing threats from climate change and deforestation. Land 7(3):90. https://doi.org/10.3390/land7030090

Thornton D, Branch L, Murray D (2020) Distribution and connectivity of protected areas in the Americas facilitates transboundary conservation. Ecol Appl 30(2). http://doi.org/10.1002/EAP.2027

UNEP-WCMC (2016) The state of biodiversity in Latin America and the Caribbean: a mid-term review of progress towards the Aichi Biodiversity Targets. UNEP-WCMC, Cambridge, UK

United Nations General Assembly (UNGA) (2012) A/RES/66/288: The future we want. United Nations. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_66_288.pdf

Veblen T, Young K, Orme A (eds) (2007) The physical geography of South America. Oxford University Press. http://doi.org/10.1093/oso/9780195313413.001.0001

Vicuña S, Gil M, Melo O, Donoso G, Merino P (2018) Water option contracts for climate change adaptation in Santiago, Chile. Water Int 43(2). http://doi.org/10.1080/02508060.2017.1416444

Walker R, Moore NJ, Arima E, Perz S, Simmons C, Caldas M, Vergara D, Bohrer C (2009) Protecting the Amazon with protected areas. Proc Natl Acad Sci 106(26):10582–10586. https://doi.org/10.1073/PNAS.0806059106

WMO (2021) State of the climate in Latin America and the Caribbean, WMO-No. 1272. https://library.wmo.int/doc_num.php?explnum_id=10876

Zambrano L, Pacheco-Muñoz R, Fernández T (2017) A spatial model for evaluating the vulnerability of water management in Mexico City, Sao Paulo and Buenos Aires considering climate change. Anthropocene 17. https://doi.org/10.1016/j.ancene.2016.12.001

Cristián Bonacic has a B.Sc. in Veterinary Medicine, a M.Sc. in Wildlife Management and Control (University of Reading), and a Ph.D. in Zoology (University of Oxford). He is a Professor of wildlife ecology and management in the School of Agriculture and Forest Sciences and the School of Veterinary Medicine (Pontificia Universidad Católica de Chile). He is also Director of the Fauna Australis wildlife Conservation Research Laboratory. He is a member of the IUCN South American Camelids specialists group.

Constanza Arévalo holds a M.Sc. degree in Natural Resources (Pontificia Universidad Católica de Chile) and a BA degree in German Studies and Biological Sciences (Cornell University). She has been an Associate Researcher of the Fauna Australis Wildlife Conservation Laboratory since 2018. Constanza's main line of research has concerned anthropogenic influences on urban birds in Santiago de Chile, but she has also collaborated on works involving human-carnivore conflicts in Mesoamerica and the role of protected areas in Latin America.

José Tomás Ibarra has a B.Sc. in Agronomy, a M.Sc. in Natural Resources (Pontificia Universidad Católica de Chile), a M.Sc. in Environmental Anthropology (University of Kent), and a Ph.D. in Forest Sciences (University of British Columbia). He is an Associate Professor on Human Ecology and Social-Ecological Systems at Pontificia Universidad Católica de Chile and Director of ECOS (Ecosystem-Complexity-Society) Co-Laboratory.

Jerry Laker has a B.Sc. in Agriculture (University of Liverpool) and a M.Sc. in Ecology (Bangor University). He is a field ecologist and Conservationists and the Director of Kod Kod Field Research Station in the temperate rainforests of southern Chile. He is a former researcher at Macaulay Land Use Research Institute in Scotland.

Impacts of Climate Change on Biodiversity Resources, Especially Forests and Wildlife Distribution

Muhammad Nawaz Rajpar, Mirza Barjees Baig, Mohamed Behnassi, and Michael Robert Reed

Abstract Climate change refers to significant changes in weather as a result of natural and anthropogenic factors with direct or indirect impacts on forest vegetation structure and wildlife distribution. This is the significant environmental challenge in the current scenario that poses serious threats to biodiversity, particularly forests and wildlife resources. Wildlife is interrelated with weather conditions that affect the distribution of vegetation and the shape of habitat that supports the broad range of wildlife species. Climate change negatively affects forestry ecosystem functions by affecting productivity, biomass, and trophic interactions. It intensifies the natural balance of flora composition and vegetation structure, which ultimately affects the distribution of home ranges and habitat use of wildlife species. Wildlife is susceptible to climatic factors, such as temperature, evapotranspiration, light intensity, and relative humidity. Falling and rising temperatures affect forest plant growth, flowering, and fruiting seasons. Vegetation alteration influences the distribution and behavior of wildlife species, such as migration, reproduction cycle, forging, habitat selection, reproductive success, and nesting activities of wildlife species. Therefore,

M. N. Rajpar (✉)
Department of Forestry, Faculty of Life Sciences, Shaheed Benazir Bhutto University, Sheringal, Upper Dir, Pakistan
e-mail: rajparnawaz@sbbu.edu.pk

M. B. Baig
Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riyadh, Kingdom of Saudi Arabia
e-mail: mbbaig@ksu.edu.sa

M. Behnassi
Senior Environmentalist Expert, Economic Social & Environmental Council (ESEC), Rabat, Morocco
e-mail: m.behnassi@uiz.ac.ma

Director, Center for Environment, Human Security and Governance (CERES), Rabat, Morocco

M. R. Reed
Professor Emeritus of Economics, University of Kentucky, Lexington, USA
e-mail: mrreed@email.uky.edu

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_4

determining the impacts of climate change on forests and wildlife resources is of paramount importance since it provides insight into how these various factors affect biodiversity resources. In addition, it will assist in formulating an appropriate strategy for the management and conservation of forest and wildlife resources.

Keywords Biodiversity · Birds · Climate · Environment · Forest · Habitat · Mammals · Vegetation

1 Introduction

Biodiversity is vital for the existence and survival of human beings on the earth. It protects from hurricanes, stores carbon, purifies water, releases oxygen, absorbs CO_2, and balances the proper functions of the biosphere. In the absence of diverse ecosystems, the life of human beings may be in danger and threatened (Blogger 2018). Around the world, biodiversity resources, especially forests and wildlife, are being lost and threatened due to human interactions (Bellard et al. 2012; Barlow et al. 2018; Brito-Moreales et al. 2018; Fardila et al. 2017). In this context, climate change is currently one of the serious and major threats to biodiversity loss (Guo et al. 2017; Matata and Adan 2018; Pacifici et al. 2015; Sonwa et al. 2017) since its impacts contribute to the displacement of wildlife species and making their habitats unsuitable (Fereja 2017; Hussain et al. 2020; Khan and Baig 2020; Lashari et al. 2020). Climate change impacts alter the composition of plant species, reduce food resources, and disturb breeding grounds, which in the end reduce bird populations (Baig and Aldosari 2012; Lafferty 2009; Lebreton 2011; Sintayehu 2018; Zong and Wang 2017), reduce food availability and productivity (Aryal et al. 2019; Paustaso et al. 2010; Sommer et al. 2010), shift home range distribution (Araujo et al. 2011; Chen et al. 2011; Loss et al. 2011), change breeding behavior (Leech et al. 2004; Przybylo et al. 2000), alter migration ecology (Rivalan et al. 2007; Visser et al. 2009; Wanless et al. 2009; Lehikoinen and Sparks 2010), and change population structure (Walther 2010) of various wildlife species (Clavero et al. 2011; Dawson et al. 2011; Fenoglio et al. 2010).

Climate change enhances greenhouse effects that directly or indirectly alter the forest vegetation and wildlife population across the world through fluctuations in temperature (Baig et al. 2020), relative humidity, evapotranspiration, and precipitation. These factors significantly influence vegetation structure and species composition and thus, ultimately increase or decrease productivity. Habitat productivity plays a crucial role in harboring the fauna to utilize it in order to perform multiple activities. Climate change reduces the population of wildlife, fauna, and forest resources, thus increasing biodiversity loss, desertification, land degradation, and malnutrition (FAO 2018; Reed and Stringer 2015; Rosenzweig and Neofotis 2013; Scheidel and Work 2018). Climate change may cause shifts in habitats, thus reducing their productivity, especially in warmer habitats due to heat and water stress (Challinor et al. 2014; Lobell et al. 2011; Pimm et al. 2014).

Global warming causes more frequent floods, droughts, and heavy rains; depleted water tables; increased vulnerability of ecosystems to diseases; reduced food resources; and lowered productivity and habitat suitability for wildlife species. However, the effects of climate change vary according to each ecosystem, habitat, and region. For example, the rise in temperature increases the productivity of cooler habitats (Moore and Lobell 2015). Ali et al. (2017) state that climate change causes extreme weather conditions that result in forest losses through heat waves and wildfires that burn vegetation and affect wildlife populations. The intensity of wildfires and longer droughts cause, in turn, land degradation and mortality of vegetation (Allen et al. 2010; Anderegg et al. 2012; Scheidel and Neofotis 2013).

Uncontrolled human activities—i.e., deforestation, burning of fossil fuel, land degradation practices, and pollution—have altered the proportion of gases in the atmosphere and caused global warming (Surasinghe 2010; Baig and Al-Subaiee 2011). These emissions are the major factors that negatively affect biodiversity resources, particularly by decreasing forest cover and changing the behavior of wildlife species (Berry and Roderick 2002). These factors have imposed serious physiological and environmental stress on the forest ecosystems and render it unfit to harbor wildlife species (Ansari and Golabi 2019; Hughes et al. 2020). Furthermore, they adversely affect habitat use by wildlife species, home range distribution, foraging behavior, reproductive cycles, and migration patterns. This alteration in climatic conditions has disturbed the dynamic equilibrium of habitats and their productivity (e.g., biomass, hydrology, food productivity, and livelihood of forest-dependent local communities).

It has been stated that some wildlife species have lost much of their native habitat and experienced a reduction in their geographical range, making them highly vulnerable to extinction. However, the effects of climate change vary according to each species, with some species (i.e., Key Deer—*Odocoileus virginianus clavium)* more susceptible and less resilient to such effects (Hilbert et al. 2004; Lovejoy 2008). The details of climate change effects on wildlife are given below.

2 Impacts of Climate Change on Vegetation Structure and Composition

The vegetation structure and composition determine the relevance and productivity of habitat to bird species. Climate change alters the habitat quality that indicated the reproduction and survival rate of avian species (Desgranges et al. 2006; Hayhoe et al. 2007). Poor habitat quality results in low fecundity and recruitment, which cause a reduced population (Sillett and Holmes 2002; Nagy and Holmes 2005). The habitat loss and disturbance have effects on foraging behavior, time of migration, and breeding. Notably, climate change impacts, particularly the alteration of temperature and humidity patterns, directly and indirectly affect the growth and reproduction of vegetation (Fig. 1). For example, the rise in temperature creates warmer weather conditions that cause a shift in vegetation for the higher elevations.

The rise in temperature causes the melting of glaciers that ultimately increases the sea level, hence causing frequent flooding of the coastal areas. Saltwater intrusion has caused vegetation stress that affects their growth, and some species may not be able to survive on high salt content. This stress will exert a cumulative impact that leads to dramatic ecological changes in the food chain and vegetation structure. Climate change potentially affects vegetation structure and functions of temperate, boreal and tundra, and tropical and sub-tropical forests (Knapp et al. 2008). For example, boreal and temperate forests are replaced by scrub at a lesser extent (Dullinger et al. 2004). Ecosystems are increasingly vulnerable to loss and disturbances due to the impacts of climate change.

Climate change will also cause negative effects on blooming, flowering, and the reproductive cycle of vegetation. It will increase the risk of drought that makes ecosystem susceptible to fire. Thus, the vegetation becomes less resilient and more vulnerable to easy attack of insects that defoliate and weaken the tree, outbreaks of wildfire that burn sensitive vegetation, and storms that uproot and damage vegetation. The rise in temperature enhances the extent and intensity of droughts which decrease the productivity of a particular areas. On the other hand, it also causes water scarcity due to which woody vegetation becomes dry and susceptible to fires and modifies the functions of the forest ecosystem. For example, prolonged drought alters vegetation structure, such as converting forest into scrublands and grasslands (Neelin et al. 2003).

Climate change inevitably affects birds and mammals at higher altitude due to the alteration in the thermal range (Beever et al. 2003). For example, temperature

Fig. 1 Effects of climate change on vegetation structure. https://www.scmp.com/lifestyle/arts-culture/article/3016467/best-climate-change-fiction-books-overstory-flight-behaviour

rises due to climate change may cause severe weather conditions that affect the food resources and reduce forest productivity through changing biotic factors. The abiotic factors, such as light, water, precipitation, and temperature, significantly influence the growth and reproductive cycle of trees, shrubs, herbs, forbs, and grasses. This, in turn, reduces productivity and modifies species composition, i.e., colonized species, and creates a new forest ecosystem. Furthermore, climate change favors invasive species which become tolerant, thus dominating and suppressing native plants.

3 Climate Change Impacts on Different Wildlife Fauna Species

Climate change is already causing increased fluctuations in temperature and precipitation, which directly or indirectly affect wildlife home range, tolerance, and migration. Temperature and relative humidity alter food resources, reproductive cycles, and movement of wildlife fauna. The increase in temperature causes drought, resulting in water and food scarcity. These changing dynamics ultimately affect wildlife health.

3.1 Climate Change Impacts on Amphibians

It has been stated that over 70% of amphibian species have declined due to the impacts of climate change and human interventions (Hayes et al. 2010; Ochoa-Ochoa et al. 2012; Roelants et al. 2007; Zhang et al. 2012). Around 32% of amphibian species are at risk of extinction, 43% are threatened, and 22% are data deficient (Hof et al. 2011; Stuart et al. 2004; Wake and Vredenburg 2008). The major factors that have caused this decline in the populations of amphibians are habitat loss and degradation (Eignbbrod et al. 2008; Harper et al. 2008; Sheriff et al. 2009), over-exploitation (Stuart et al. 2004), and climate change (Carey and Alexander 2003; Corn 2005).

Climate change alters the hydro-period that has a significant influence on the activities of amphibians. They are less resistant to falling and rising temperatures and are at greater risk. Climate change has caused a drier and frozen environment that intensifies effects on the home range and survival of amphibians (Araujo et al. 2006; Mokhatla et al. 2015; Cunningham et al. 2016). The presence of water is vitally important for the amphibian reproduction. Amphibians cannot survive and reproduce without water—i.e., prior drought caused massive mortality of eggs, tadpoles, and metamorphosis. Furthermore, climate change is a major threat to the amphibian's survival and reproduction (Fig. 2). Drought isolates habitats so that amphibians are restricted to specific habitats that might not be suitable for them (Chen and Bi 2007; Sarmento Cabral et al. 2013; Mokhatla et al. 2015). Amphibians become more exposed to water scarcity and easily hunted by predators. Drought causes food scarcity, larval mortality, and extreme weather conditions. Prolonged droughts and unpredictable

Fig. 2 Effects of climate change on amphibians. *Source* Photograph by Joel Sartore, Nat Geo Image Collection

floods cause the loss of breeding grounds and mortality (Jones et al. 2001; Carey and Alexander 2003) and determine the distribution of amphibian species, in particular aquatic habitats (Munguia et al. 2012; Ficetola et al. 2015).

Furthermore, climate change alters the breeding behavior of amphibians that ultimately results in a decline in the density and diversity across the heterogeneous aquatic habitats (Table 1). Likewise, it negatively affects timing of breeding, egg hatching success, larval surviving rate, and the metamorphoses process (Blaustein et al. 2001). It has been reported that 1/3 of amphibian species are at risk of extinction due to temperature increases (Blaustein et al. 2001; Saenz et al. 2006). Because these species are cold blooded, they have restricted movement and cannot migrate from one habitat to another. So, they are less resilient and cannot survive in harsh weather conditions (Araujo et al. 2006; Blaustein et al. 2010; Carey and Alexander 2003; Corn 2005; Laurance 2008; Lawler et al. 2009; Milanovich et al. 2010).

3.2 Climate Change Impacts on Avian Species

Bird species inhabit the Artic, Antarctic, islands, forests, mountains, wetlands, and coastal areas. All these areas are highly vulnerable to climate change. Birds are bio-indicators of climate change (Sekercioglu et al. 2012). They are closely associated with habitat and microclimate conditions. The habitat productivity, land-use pattern, alteration in weather conditions, and food resources significantly affect the bird diversity and distribution (Rajpar and Zakaria 2011). Birds are a vitally important component of each ecosystem and play a significant role to balance ecosystems' functions. Unfortunately, they are facing overwhelming threats due to habitat loss

Table 1 Impacts of climate change on amphibian's activities

Scientific name	Common name	Effects of climate change	References
Bufo boreas	Western Toad	Breeding, mating, and spawning periods	Beebee (1995), Blaustein et al. (2001)
Pseudacris crucifer	Spring Peeper	Breeding, mating, and spawning periods	Beebee (1995), Blaustein et al. (2001)
Bufo fowleri	Fowler's Taod	Breeding, mating, and spawning periods	Beebee (1995), Blaustein et al. (2001)
Rana cascadae	Cascades Frogs	Breeding, mating, and spawning periods	Beebee (1995), Blaustein et al. (2001)
Triturus cristatus	Northern Crested Newt	Spawning migration	Dervo et al. (2016)
Lissotriton vulgaris	Smooth Newt	Spawning migration	Dervo et al. (2016)
Rana sylvatica	Wood Frog	Habitat alteration that causes reproduction failure	Hayes et al. (2010)
Ambystoma maculatum	Spotted Salamander	Habitat alteration that causes reproduction failure	Hayes et al. (2010)
Bufo boreas	Boreal Toad	Habitat alteration that causes reproduction failure	Hayes et al. (2010)
Anaxyrus boreas	Western toad	Earlier breeding	Blaustein et al. (2001)
Rana cascadae	Cascade Frog	Earlier breeding	Blaustein et al. (2001)
Pseudacris crucifer	Spring Peeper	Earlier breeding	Blaustein et al. (2001)
Bufo fowleri	Fowler's Toad	Earlier breeding	Blaustein et al. (2001)

and disturbance, rise and fall in temperature, and food resource scarcity. It has been reported that one out of every eight species is threatened and endangered (Azman et al. 2011; Vie et al. 2009) due to climate change and human interventions. Parmesan (2006) reported that 59 bird species shifted their home range northward to a warmer climate. However, some species that are unable to change their home range will perish because they are unable to adapt (Surasinghe 2010).

Climate change affects the breeding ecology of avian species by causing birds to lay their eggs earlier than usual time period (Sekercioglu et al. 2008; Gregory et al. 2009; Niven et al. 2009; Chen et al. 2011). This could be the result of the early arrival of birds to their nesting sites (Table 2). Another reason could be linked to the migration of bird species from cooler areas to the warmer habitats due to the severity of temperature (Fig. 3). The bird migration clearly indicates the impacts of climate change on bird distribution and habitat use (Figs. 4 and 5) (Lee et al. 2005; Rodenhouse et al. 2009).

Table 2 Climate change impacts on birds' activities

Scientific name	Common name	Effects of climate change	References
Cuculus canorus	Common Cuckoo	Delayed arrival to breeding grounds	Valiela and Bowen, (2003), Gordo et al. (2005)
Apus apus	Common Swift	Delayed arrival to breeding grounds	Gordo et al. (2005)
Upupa epops	Eurasian Hoopoe	Delayed arrival to breeding grounds	Gordo et al. (2005)
Hirundo rustica	Barn Swallow	Delayed arrival to breeding grounds	Gordo et al. (2005)
Delichon urbica	Common House Martin	Delayed arrival to breeding grounds	Gordo et al. (2005)
Luscinia megarhynchos	Common Nightingale	Delayed arrival to breeding grounds	Gordo et al. (2005)
Aptenodytes forsteri	Emperor Penguin	Habitat degradation and population decline	Barbraud and Weimerskirch (2001)
Pygoscelis adeliae	Adelie Penguin	Habitat degradation and population decline	Barbraud and Weimerskirch (2001)
Toxostoma guttatum	Cozumel Thrasher	Home range distribution	Marini et al. (2009)
Afropavo congensis	Congo Peafowl	Home range distribution	Marini et al. (2009)
Cnipodectes superrufus	Rufous Twistwing	Home range distribution	Marini et al. (2009)
Nothura minor	Lesser Nothura	Home range distribution	Marini et al. (2009)
Camarhynchus heliobates	Mangrove Finch	Habitat loss and degradation	Waycott et al. (2009)
Papasula abbotti	Abbott's Booby	Habitat loss and degradation	Waycott et al. (2009)
Platalea ajaja	Roseate Spoonbills	Diversity pattern	Traill et al. (2010), Garnett and Brook (2007)
Mycteria americana	Wood Stork	Diversity pattern	Traill et al. (2010), Garnett and Brook (2007)
Cisticola aridulus	Desert Cisticola	Extreme weather conditions	Schneider and Griesser (2009)
Tangara icterocephala	Silver-throated Tanagers	Habitat alteration	Sekercioglu et al. (2007), Felton et al. (2009)
Catharus aurantiirostris	Orange-billed Nightingale-thrush	Habitat alteration	Sekercioglu et al. (2007), Felton et al. (2009)

(continued)

Table 2 (continued)

Scientific name	Common name	Effects of climate change	References
Turdus assimilis	White-throated Thrush	Habitat alteration	Sekercioglu et al. (2007), Felton et al. (2009)
Merops revoilii	Somali Bee-eater	Physiological adaptation	Weathers et al. (2001)
Sporophila aurita	Seed-eater	Physiological adaptation	Weathers et al. (2001)
Nectarinia senegalensis	Silver-throated Tanager	Temperature tolerance	Seavy (2018)
Tangara icterocephala	Silver-throated Tanager	Foraging behavior	Sekercioglu et al. (2007)
Sylvia curruca	Lesser Whitethroat	Home range reduction	Doswald et al. (2009)
Sylvia borin	Garden Warbler	Home range reduction	Doswald et al. (2009)
Catharus mexicanus	Black-headed Nightingale Thrush	Shift in home range	Jankowski et al. (2010)
Polioptila californica	California Gnatcatcher	Habitat suitability	Preston et al. (2008)
Parus major	Great Tit	Food supply, breeding grounds, nesting behavior, egg hatching success, juvenile survival population decline	Visser et al. (1998), Pearson and Dawson (2003), Both et al. (2006), Ahola et al. (2007)
Catharus bicknelli	Bicknell's Thrush	Habitat shift	Rodenhouse et al. (2008)
Dendroica careulescens	Black-throated Blue Warbler	Habitat quality	Rodenhouse et al. (2008)
Hylocichla mustelina	Wood Thrush	Population decline	Rodenhouse et al. (2008)
Icterus galbula	Baltimore Oriole	Population decline	Rodenhouse et al. (2008)
Bonasa umbellus	Ruffed Grouse	Population decline	Rodenhouse et al. (2008)
Poecile atricapilla	Black-capped Chickadee	Population decline	Rodenhouse et al. (2008)
Botaurus lentiginosus	American Bittern	Population decline	Rodenhouse et al. (2008)
Gavia immer	Common Loon	Population decline	Rodenhouse et al. (2008)
Porzana Carolina	Sora Rail	Population decline	Rodenhouse et al. (2008)
Butorides virescens	Green Heron	Population increase	Rodenhouse et al. (2008)
Ardea albus	Great Egret	Population increase	Rodenhouse et al. (2008)

(continued)

Table 2 (continued)

Scientific name	Common name	Effects of climate change	References
Bubulcus ibis	Cattle Egret	Population increase	Rodenhouse et al. (2008)
Pica pica	Magpie	Early nesting	Crick (2004)
Miliaria calandra	Corn Bunting	Late nesting	Crick (2004)
Ardea cinerea	Grey Heron	Population decline	Marchant et al. (2004)
Ficedula albicollis	Collard Flycatcher	Breeding ecology, i.e., egg-laying and clutch size	Przybylo et al. (2000)
Uria aalge	Common Guillemot	Food availability	Leech et al. (2004)
Rissa tridactyla	Kittiwake	Food availability	Leech et al. (2004)
Charadrius hiticula	Ringed Plover	Shift in distribution	Leech et al. (2004)
Calidris alpine	Dunlin	Shift in distribution	Leech et al. (2004)
Phoenicurus ochruros	Black Redstart	Shift in distribution	Leech et al. (2004)
Cettia cetti	Cetti's Warbler	Shift in distribution	Leech et al. (2004)
Certhia familiaris	Treecreeper	Survival rate	Leech et al. (2004)
Gallinago gallinago	Snipe	Reduced food availability	Leech et al. (2004)
Nummenius arquata	Curlew	Reduced food availability	Leech et al. (2004)
Turdus merula	Blackbird	Reduced food availability	Leech et al. (2004)
Turdus philomelos	Song Thrush	Reduced food availability	Leech et al. (2004)
Phoenicurus phoenicurus	Common Redstart	Migration behavior	Leech et al. (2004)
Ficedula hypleuca	Pied Flycatcher	Migration behavior	Leech et al. (2004)
Lagopus mutus	Ptarmigan	Loss of species due to restriction of breeding grounds	Leech et al. (2004)
Plectrophenax nivalis	Snow Bunting	Loss of species due to restriction of breeding grounds	Leech et al. (2004)
Cygnus Cygnus	Whooper Swan	Loss of species due to restriction of breeding grounds	Leech et al. (2004)
Stercorarius parasiticus	Arctic Skua	Loss of species due to restriction of breeding grounds	Leech et al. (2004)

(continued)

Table 2 (continued)

Scientific name	Common name	Effects of climate change	References
Tringa nebularia	Greenshank	Loss of species due to restriction of breeding grounds	Leech et al. (2004)
Calidris alba	Sanderling	Loss of species due to restriction of breeding grounds	Leech et al. (2004)
Calidris maritima	Purple Sandpiper	Loss of species due to restriction of breeding grounds	Leech et al. (2004)
Calidris canuta	Knot	Reduced breeding grounds	Leech et al. (2004)
Anser fabalis	Bean Goose	Reduced breeding grounds	Leech et al. (2004)
Hirundo rustica	Barn Swallow	Reduced food availability and population size	Leech et al. (2004)
Sylvia communis	Common Whitethroat	Reduced food availability and population size	Leech et al. (2004)
Acrocephalus schoenobaenus	Sedge Warbler	Reduced food availability and population size	Leech et al. (2004)

Fig. 3 Climate change impacts on bird habitat use and distribution. *Source* Photo by Courtesy of Lee Tiak

Fig. 4 Climate change impacts on bird distribution. *Source* Photo by Muhammad Nawaz Rajpar

Fig. 5 Climate change impacts on bird distribution and habitat use. *Source* Photo by Muhammad Nawaz Rajpar

Most tropical bird species may be endemic to mountain and low-lying habitats (Loarie et al. 2009). They become easily vulnerable and less resilient as a result of climate change (LaSorte and Jetz 2010; Harris et al. 2011). It has been reported that the rise and fall in temperature due to climate change have altered the migration period, time of breeding, and survival rate (Crick 2004; Devicot et al. 2008; Gilyazov and Sparks 2002; Huppop and Huppop 2003; Sparks and Mason 2001).

3.3 Climate Change Impacts on Mammal Species

Mammals are crucial components of the food chain and food web. They perform important roles to balance the particular ecosystem. They are major sources of food for a wide array of animals as preys and also predators that kill and consume some other animals to balance the ecosystem function—i.e., control pest population, disperse seed, control vegetation, and pollinate flowers. Hence, they have profound impacts on ecosystem functions. Climate change alters microclimate conditions that result in drought, severe or unusual cold or heat, and storms that have negative effects on the ecological niche of mammal species (Levinsky et al. 2007; Mckelvey et al. 2011). In addition, they interact with other wildlife species in symbiotic association.

Mammals are negatively impacted by human interventions, i.e., habitat loss and fragmentation due to deforestation and land degradation, over-exploitation (uncontrolled hunting), introduction of invasive species, and pollution and climate change which have reduced the population of carnivore and ungulate mammals (Hoffmann et al. 2010; IUCN 2018; Newbold 2018). It has been reported that 1141 out of 5487 mammal species are at risk of extinction, 188 mammal species are critically endangered, and 29 mammal species are already extinct (Di Marco et al. 2018; IUCN 2008). In addition, 50% of all primates and 36% marine mammals are threatened (Redford et al. 2011).

Most mammal species are mobile and can migrate when scarcity of food and severe weather conditions become an issue (Pearson and Dawson 2003). However, some mammal species have a narrow range of distribution and food resources—e.g., polar bears, snow leopards, pika, seals, and wolverines (Beever et al. 2011; Ripple et al. 2010). These species are at higher risks due to climate change. Climate change directly and indirectly affects diverse activities of mammalian species. Climate change causes range shifts, relative regional abundance, diversity indices, and population structures (Carroll et al. 2014; Laidre et al. 2015; Poloczanska et al. 2016; Schumann et al. 2013; Walsh et al. 2015).

They need a specific environment to carry out multiple activities, such as shelter from predators and harsh weather conditions, drinking water, and appropriate breeding grounds to increase their population (Fig. 6 and Table 3).

3.4 Climate Change Impacts on Reptilian Species

Reptiles—e.g., snakes, lizards, crocodiles, and turtles—are fundamental components of ecosystems and play a crucial role in their proper functioning. Reptiles are key animals of the food chain and food web that balance the population of small animals, such as insects, rodents, birds, and small mammal, and serve as food for other predator animals, such as birds and mammals. Unfortunately, these animals are facing severe threats due to anthropogenic activities—i.e., habitat alteration, illegal trapping for

Fig. 6 Effects of climate change on water resources. *Source* Photo by Martin Harvey/WWF-Canon. © Martin Harvey/WWF-Canon

food and pet purposes—and climate change (Klemens and Thorbjarnarson 1995; McKinny 2008; Witczak and Dorcas 2009).

Reptiles are the most sensitive to temperature alteration (Figs. 7 and 8) because they modify their ectothermic activities based on temperature fluctuation. Thus, they maintain their physiological processes through the regulation of body temperature by taking a sunbath, cooling off in the shade, or burrowing in soil. Climate change potentially affects movement, home range, and reproduction and foraging activities (Table 4). In temperate habitats, reptiles are highly vulnerable to the impacts of climate change (Araujo et al. 2006; Gibbons et al. 2000; Huey et al. 2009; Newbold 2005).

The population of reptiles has significantly declined due to climate change (Clusellaa–Trullas et al. 2011; Sinervo et al. 2010; Webb et al. 2008), which affects the quality of their habitat (Morelli et al. 2017); their activities such as reproduction, foraging, mating, and egg-laying (Huang et al. 2013); the population structure (Lukoschek et al. 2013; Pomara et al. 2014); and species composition (Lemes and Loyola 2013) and distribution (Ferro et al. 2014). All these factors make them more vulnerable, threatened, and endangered (Fig. 9). There are many functions of reptile species that are closely associated temperature and relative humidity (climate regime and severity of threats).

Because reptiles' activities are closely related to microclimates and restricted to a particular habitat, fluctuation in microclimate conditions may cause reproductive failure (Monasterio et al. 2013; Dayananda et al. 2016). For example, a rise in temperature enhances the activities of reptiles while a fall in temperature reduces them; some species hibernate due to severe cold (Wake 2007; Moreno–Rueda et al. 2011; Zani and Rollyson 2011).

Table 3 Climate change impacts on mammalian's activities

Scientific name	Common name	Effects of climate change	References
Tamiasciurus hudsonicus	Canadian Red Squirrel	Mating behavior	Reale et al. (2003)
Ursus maritimus	Polar Bear	Prey	Ferguson et al. (2005)
Marmota flaviventris	Yellow-bellied Marmots	Exit from overwintering	Inouye et al. (2000)
Cervus elaphus	Red Deer	Range expanded	Lister and Stuart (2008)
Rangifer tarandus	Reindeer	Shift in range area	Lister and Stuart (2008)
Equus ferus	Wild Horse	Contraction in range	Lister and Stuart (2008)
Coelondonta antiquitatis	Woolly Rhinoceros	Distribution	Lister and Stuart (2008)
Megaloceros gignateus	Giant Deer	Complex distributional change in home range	Lister and Stuart (2008)
Panthera spelaea	Eurasian Cave Lion	Population isolation due to non-migration	Lister and Stuart (2008)
Phoca largha	Spotted Seals	Migration pattern	
Erignathus barbatus	Beard Seal	Migration behavior	Crawford et al. (2015)
Eumetopias jabatus	Steller Sea Lion	Shift in range	Crawford et al. (2015)
Orcinus orca	Killer Whale	Foraging behavior	Moore and Huntington (2008)
Pusa hispida	Ringed Seal	Shift in range	Crawford et al. (2015)
Ursus maritimus	Polar Bear	Shift in range and food distribution	Huntington et al. (2016)
Megaptera novaeangliae	Humpback Whale	Shift in range and food distribution	Moore and Huntington (2008)
Balaenoptera physalus	Fin Whale	Shift in range and food distribution	Moore and Huntington (2008)
Balaena mysticetus	Bowhead Whale	Shift in range	George et al. (2015)
Dicrostonyx groenlandicus	Northern Collard Lemming	Habitat loss	Kerr and Packer (1998)
Ursus americanus	American Black Bear	Habitat loss	Kerr and Packer (1998)
Oryx dammah	Scimitar-horned Oryx	Shift in range	Hetem et al. (2014)

(continued)

Table 3 (continued)

Scientific name	Common name	Effects of climate change	References
Vulpes vulpes	Red Fox	Decreased in distribution range	Hetem et al. (2014)
Alopex lagopus	Arctic Fox	Increase interspecies competition in food and space	Hetem et al. (2014)
Ovis Canadensis nelson	Desert Bighorn Sheep	Alter habitat and decline population	Hetem et al. (2014)
Rangifer tarandus	Reindeer	Calf mortality and trophic mismatch	Hetem et al. (2014)
Antilocapra americana	Pronghorn	Shift life history	Hetem et al. (2014)
Lutra lutra	Eurasian Otter	Body size	Hetem et al. (2014)
Oryx leucoryx	Arabian Oryx	Shift in range	Hetem et al. (2014)
Gazella subgutturosa marica	Arabian Sand Gazelle	Shift in range	Hetem et al. (2014)
Sorex araneus	Common Shrew	Effects on food availability	Levinsky et al. (2007)
Sorex minutus	Pygmy Shrew	Effects on food availability	Levinsky et al. (2007)

Fig. 7 Climate change impacts on reptile home range *Source* https://www.desertsun.com/story/news/environment/2014/06/07/climate-change-california-desert-animals/10035779/

4 Solutions to Mitigate Climate Change Impacts

Forests play a crucial role in mitigating the impacts of climate change as 'sinks' through the absorption of carbon dioxide from the atmosphere (i.e., 638 billion tons in 2019) and storing it as biomass (44%), soil (46%), dead wood (6%), and litter (4%)

Fig. 8 Climate change impacts on reptile home range. *Source* https://sustain.round.glass/species/fan-throated-lizards-a-flash-of-fabulous/#images-1

Table 4 Climate change impacts on reptilians' activities

Scientific name	Common name	Effects of climate change	References
Xenosaurus tzacultipantecus	Knob-scaled Lizard	Decreased habitat suitability	Berriozabal–Islas et al. (2018)
Oedura lesurii	Velvet Gecko	Population structure	Webb et al. (2008)
Phalotris lemniscatus	Dumeril's Diadem Snake	Reduced home range	Lourenco-de-Moraes et al. (2019)
Clelia hussami	Mussurana Snake	Reduced home range	Lourenco-de-Moraes et al. (2019)
Drymarchon corais	Indigo Snake	Expand geographical range	Lourenco-de-Moraes et al. (2019)
Xendon merremii	Wagler's Snake	Expand geographical range	Lourenco-de-Moraes et al. (2019)
Bothrops pirajai	Piraja's Lancehead Snake	Reduced home range	Lourenco-de-Moraes et al. (2019)
Corllus cropanni	Cropan's Tree Boa	Reduced home range	Lourenco-de-Moraes et al. (2019)
Chironius carinatus	Amazon Whip Snake	Threat of increased heat effect	Lourenco-de-Moraes et al. (2019)
Trimeresurus gracilis	Taiwan Pit Viper	Threatened warmer effect	Huang et al. (2013)

to stabilize the climate system and regulate the environment. In addition, forests are hotspots of biodiversity resources and are an ideal home for a wide array of flora and fauna species that humans utilize on a daily basis for food, shelter, clothing, and medicines. These biodiversity resources can be protected, inter alia, through the

Fig. 9 Climate change as a factor of reptile mortality. https://news.fsu.edu/wp-content/uploads/2019/09/Fuentes-loggerheadWEB.jpg

establishment of protected areas, such as national parks, wildlife sanctuaries, game reserves, nature parks, protected forests, and reserve forests.

Once forests are cleared or degraded, they emit huge amounts of greenhouse gases (mainly CO_2, N_2O, CH_4, and CFCs) into the atmosphere that are a major cause of climate change. Climate change has increased the vulnerability of forest animals and communities that depend on forests. However, the impacts of vulnerability vary geographically, resiliently, and adaptably. To reduce the impacts of climate change, the integrity, health, and resilience of forest ecosystems should be preserved. Forest resources should be managed sustainably in order to help reduce the adverse impacts of climate change on biodiversity resources, forest-dependent communities, and food security. Furthermore, deforestation should be halted and degraded areas should be restored and managed sustainably. This will help decrease biodiversity loss and mitigate climate change.

5 Important Steps to Halt Climate Change Impacts

It is strongly recommended that some preventive measures should be taken immediately to halt the loss of biodiversity and mitigate the impacts of the climate change. Some of them are given below:

- **Increase vegetation cover**: Plantation, seed broadcasting, and sustainable use of forest resources have the potential to increase the vegetation cover and improve habitat quality to harbor the higher diversity and greater populations of the heterogeneous wildlife species.

Source https://www.ecowatch.com/planting-trees-climate-crisis-2645536299.html?rebelltitem=2#rebelltitem2

- **Declare protected forests**: This measure will help stop deforestation and the decline of carbon sequestration capacity of forests. CO_2 emissions make a significant contribution to climate change.

Source https://s3.wp.wsu.edu/uploads/sites/609/2019/07/forest-1188x792.jpg

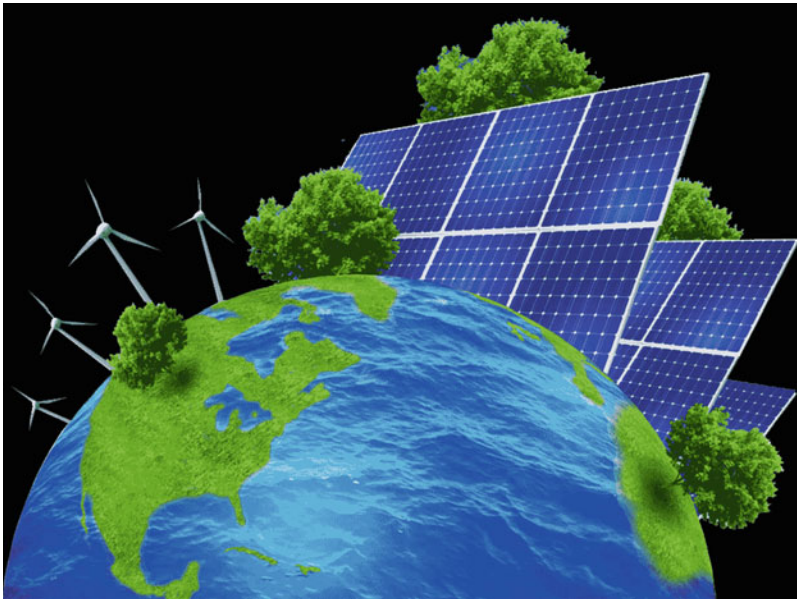
- **Establish biodiversity and climate change resource centers**: These centers should be set up across the country to provide education and foster awareness on how to mitigate climate change and protect biodiversity. Such centers may provide as well information on biodiversity resources, in particular forestry and wildlife, the effects of biodiversity loss, and the causes of climate change.

Source https://news.cgtn.com/news/3d3d414e7a456a4e77457a6333566d54/img/716fdb2fa77e-4805bd15b3757d3d7366/716fdb2fa77e4805bd15b3757d3d7366.jpg

- **Protect wildlife fauna and its habitats**: Wild fauna and flora are of crucial importance for human existence and survival. Unfortunately, because of human intervention and climate change, wild fauna and flora face immense threats related to habitat loss, food shortages, illegal poaching, and uncontrolled hunting. Because of these factors, the wildlife population has declined worldwide. Protected areas such as national parks, wildlife refuges, game reserves, biodiversity reserves, and natural parks should be established to increase wild fauna and flora populations and restore their habitats.

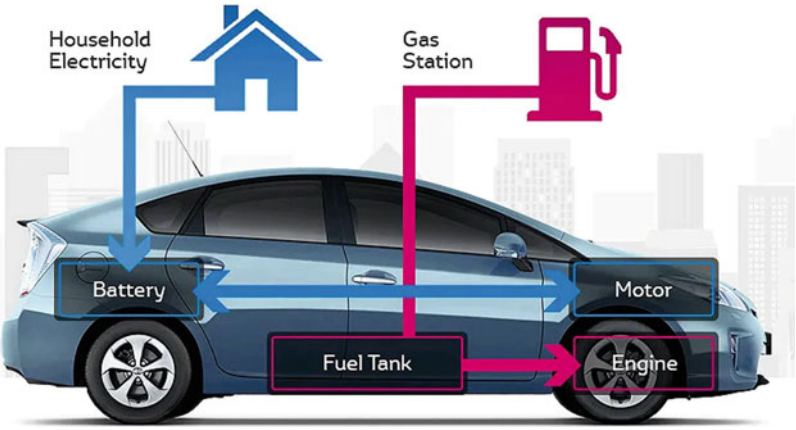
Source https://media.greenmatters.com/brand-img/eyO2mL-PN/0x0/three-types-of-biodiversity-1588691577384.jpg

- **Use renewable energy**: Solar, wind, hydropower, etc., should be widely used, for instance, in cooking and heating, to replace fossil fuels. As a result, CO_2, N_2O, CH_4, and CFC emissions to the atmosphere will be reduced.



Source http://reap.org.pk/wp-content/uploads/2019/10/solar-layer-min.png

- **Collaborate with all stakeholders**: The collaboration between governmental agencies, planners, policymakers, NGOs, foresters, researchers, environmentalists, civil society, promoters, and local communities should be enhanced in order to develop effective climate mitigation strategies.
- **Use hybrid vehicles**: Hybrid vehicles and liquefied petroleum gas (LPG) need to be used to reduce the consumption of fossil fuels and the concentration of greenhouse gases in the atmosphere.



Source http://www.rapidrepairautocenter.com/the-pros-cons-of-hybrid-cars/

6 Conclusion

This review clearly demonstrated that wildlife faces the devastating impacts of climate change, which affect the habitat structure, productivity, range distribution, migration behavior, population parameters, and wildlife reproductive cycles. Rising and falling temperatures have caused infrequent droughts which increase the mortality of wildlife, the risk of fire, and the shrinking of habitats. Climate change is also increasing the number of floods caused by particularly heavy rainfalls that disturb habitat and displaces wildlife, especially mammals, reptiles, and amphibians. These floods also affect the structure and composition of vegetation and reduce habitat suitability and productivity. Habitat quality and productivity are critical factors that sustain the wide range of wildlife species. The effects of climate change can be halted through an increased vegetation cover, less consumption of fossil fuels, the promotion of renewable energies, and the development of green and sustainable transport.

References

Ahola MP, Laaksonen T, Eeva T, Lehikoinen E (2007) Climate change can alter competitive relationship between resident and migratory birds. J Anim Ecol 78:1045–1052

Ali A, Rahut DB, Mottaleb KA, Erenstein O (2017) Impacts of changing weather patterns on smallholder well-being: evidence from the Himalayan region of northern Pakistan. Int J Clim Change Strat Manage 9:225–240

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier TM, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Xhang Z, Castro J, Demidova N, Lim J-H, Allard G, Running SW, Semerci A, Cobb N (2010) A global overview of drought and

heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manage 259:660–684
Anderegg WRL, Kane JM, Anderegg LDL (2012) Consequences of widespread tree mortality triggered by drought and temperature stress. Nat Clim Change 3:30–36
Ansari A, Golabi MH (2019) Using ecosystem services modeler (ESM) for ecological quality, rarity and risk assessment of the wild goat habitat in the Hafted-Gholleh protected area. Int Soil Water Cons Res 9:346–353
Araujo MB, Thuiller W, Pearson RG (2006) Climate warming and the decline of amphibians and reptiles in Europe. J Biogeogr 33:1712–1728
Araujo MB, Alagador D, Cabeza M, Nogues-Bravo D, Thuiller W (2011) Climate change threatens European conservation areas. Ecol Lett 14:484–492
Aryal JP, Sapkota TB, Khurana R, Khatri-Chettri A, Rahut DB, Jat ML (2019) Climate change and agriculture in South Asia: adaptation options in smallholder production systems. Environ Dev Sustain 22:5045–5075
Azman NM, Latif NSA, Sah SAM, Akil MAMM, Shafie NJ, Khairuddin NL (2011) Avian diversity and feeding guilds in a secondary forest, an oil palm plantation and a paddy field in riparian areas of the Kerian river basin, Perak Malaysia. Trop Life Sci Res 22(2):45–64
Baig MB, Aldosari F (2012) An investigation into the vanishing biodiversity: implications for rural extension. Bul J Agric Sci 18(3):403–409
Baig MB, Al-Subaiee FS (2011) Biodiversity in Pakistan: key issues. Biodiversity 10(4):20–29
Baig MB, Burgess PJ, Fike JH (2020) Agroforestry for healthy ecosystems: constraints, improvement strategies and extension in Pakistan. Agrofor Syst 1–19. http://doi.org/10/1007/s10457-019-00467-4
Barbraud C, Weimerskirch H (2001) Emperor penguins and climate change. Nature 411:183–186
Barlow J, Franca F, Gardner T, Hicks C, Lennox GD, Berenguer E, Castello L et al (2018) The future of hyperdiverse tropical ecosystems. Nature 559:517–526
Beebee T (1995) Amphibian breeding and climate. Nature 374: 219–220
Beever EA, Brussard PF, Berger J (2003) Patterns of apparent extirpation among isolated populations of pikas (*Ochotona princeps*) in the Great Basin. J Mammal 84:37–54
Beever EA, Ray C, Wilkening JL, Brussard PF, Mote PW (2011) Contemporary climate change alters the pace and drivers of extinction. Glob Change Biol 17:2054–2070
Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. Ecol Lett 15:365–377
Berriozabal-Islas C, Rodrigues JFM, Ramirez-Bautista A, Becerra-Lopez J, Nieto-Montes de Oca A (2018) Effects of climate change in lizards of the genus Xenosaurus (Xenosauridae) based on projected changes in climate suitability and climatic niche conservation. Ecol Evol 8:6860–6871
Berry SL, Roderick ML (2002) Estimating mixtures of leaf functional types using continental scale satellite and climatic data. Glob Ecol Biogeogr Lett 11:23–39
Blaustein AR, Belden LK, Olson DH, Green DM, Root TL, Kiesecker JM (2001) Amphibian and climate change. Conserv Biol 15(6):1804–1809
Blaustein AR, Walls SC, Bancroft BA, Lawler JJ, Searle CL, Gervasi SS (2010) Direct and indirect effects of climate change on amphibian populations. Diversity 2:281–313
Blogger G (2018) What is biodiversity and how does climate change affect it? Web Accessed on 30 Dec 2020 at https://blogs.ei.columbia.edu/2018/01/15/biodiversity-climate-change/
Both C, Bouwhuis S, Lessells C, Visser ME (2006) Climate change and population declines in a long distance migratory birds. Nature 441:81–83
Brito-Moreales I, Molinos J, Schoeman DS, Burrows MT, Poloczanska ES, Brown CJ et al (2018) Climate velocity can inform conservation in a warming world. Trends Ecol Evol 33:441–457
Carey C, Alexander MA (2003) Climate change and amphibian declines: is there a link? Divers Distrib 9:111–121
Carroll EL, Rayment WJ, Alexander AM, Baker CS, Patenaude NJ, Steel D, Constantine R, Cole R, Boren LJ, Childerhouse S (2014) Reestablishment of former wintering grounds by New Zealand southern right whales. Mar Mammal Sci 30:206–220

Challinor AJ, Watson J, Lobell DB, Howden SM, Smith DR, Chhetri N (2014) A meta-analysis of crop yield under climate change and adaptations. Nat Clim Change 4:287–291

Chen Y, Bi J (2007) Biogeography and hotspots of amphibian species of China: implications to reserve selection and conservation. Curr Sci 92(4):480–489

Chen I-C, Hill JK, Ohlemuller R, Roy DB, Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. Science 333:1024–1026

Clavero M, Villero D, Brotons L (2011) Climate change or land use dynamics: do we know what climate change indicators indicate? PLoS ONE 6:e18581

Clusellaa-Trullas S, Blackburn TM, Chown SL (2011) Climate predictors of temperature performance curve parameters in ectothermic imply complex responses to climate change. Am Nat 177:738–751

Corn PS (2005) Climate change and amphibians. Anim Biodivers Conserv 28:59–67

Crawford JA, Quakenbush LT, Citta JT (2015) A comparison of ringed and bearded seal diet, condition and productivity between historical (1957–1984) and recent (2003–2012) periods in the Alaskan Bering and Chukchi seas. Prog Oceanogr 136:133–150

Crick HQP (2004) The impacts of climate change on birds. Ibis 146(sup.1):48–56

Cunningham HR, Rissler LJ, Buckley LB, Urban MC (2016) Abiotic and biotic constraints across reptile and amphibian ranges. Ecography 39(1):1–8

Dawson TP, Jackson ST, House JI, Mace GM (2011) Beyond predictions: biodiversity conservation in a changing climate. Science 332:53–58

Dayananda B, Gray S, Pike D, Webb JK (2016) Communal nesting under climate change: fitness consequences of higher nest temperatures for a nocturnal lizard. Glob Change Biol 22:2405–2414

Dervo BK, Baerum KM, Skurdal J, Museth J (2016). Effects of temperature and precipitation on breeding migrations of amphibian species in southern Norway. Scientifica, 2016: 3174316

Desgranges J-L, Ingram J, Drolet B, Morin J, Savage C, Borcard D (2006) Modelling wetland bird response to water level changes in the Lake Ontario-St. Lawrence River hydrosystem. Environ Monit Assess 113:329–365

Devicot V, Julliard R, Couvet D, Jiguet F (2008) Birds are tracking climate warming, but not fast enough. Proc Roy Soc Bull 275:2743–2748

Di Marco M, Venter O, Poissingham HP, Watson JEM (2018) Changes in human footprint drive changes in species extinction risk. Nat Commun 9:4621

Doswald N, Willis SG, Collingham YC, Pain DJ, Green RE, Huntley B (2009) Potential impacts of climate change on the breeding and non–breeding ranges and migration distance of European Sylvia warblers. J Biogeogr 36:1194–1208

Dullinger S, Dironbock T, Grabherr G (2004) Modelling climate change–driven tree line shifts: relative effects of temperature increase, dispersal and invisibility. J Ecol 92:241–252

Eignbbrod F, Hecnar SJ, Fahrig L (2008) Accessible habitat: an improved measure of the effects of habitat loss and road on wildlife populations. Landscape Ecol 23:1659–2168

FAO (2018) The state of the world's forests 2018—forest pathways to sustainable development. Food and Agriculture Organization of the United Nations, Rome, Italy, p 139

Fardila D, Kelly LT, Moore JL, McCarth MA (2017) A systematic review reveals changes in where and how we have studied habitat loss and fragmentation over 20 years. Biol Cons 212:30–138

Felton A, Fischer J, Lindenmayer DB, Montague-Drake R, Lowe RA, Saunders D, Felton AM, Steffen W, Munro NT, Youngentob K, Gillen AR, Gibbons P, Bruzgul JE, Fazey I, Bond SJ, Elliott CP, Macdonald BCT, Porfirio LL, Westgate M, Worthy M (2009) Climate change, conservation and management: an assessment of the peer–reviewed scientific journal literature. Biodivers Conserv 18:2243–2253

Fenoglio S, Bo T, Cucco M, Mercalli L, Malacarne G (2010) Effects of global climate change on freshwater biota: a review with species emphasis on the Italian situation. Ital J Zool 77:374–383

Fereja GB (2017) The effects of climate change on rangeland and biodiversity: a review. Int J Res Granthaalayah 5(1):172–182

Ferguson NM, Cummings DA, Cauchemez S, Fraser C, Riley S, Meeyai A, Iamsirithaworn S, Bruke DS (2005) Strategies for containing an emerging influenza pandemic in Southeast Asia. Nature 437(7056):2019–2214
Ferro VG, Lemes P, Melo AS, Loyola R (2014) The reduced effectiveness of protected areas under climate change threatens Atlantic forest tiger moths. PLoS ONE 9:e107792
Ficetola GF, Rondinini C, Bonardi A, Baisero D, Padoa-Schioppa E (2015) Habitat availability for amphibians and extinction threat: a global analysis. Divers Distrib 21(3):302–311
Garnett ST, Brook BW (2007) Modelling to forestall extinction of Australian tropical birds. J Ornithol 148(Supp. 2):S311–S320
George JC, Druckenmiller ML, Laidre KL, Suydam R, Person B (2015) Bowhead whale body conditions and links to summer sea ice and upwelling in the Beaufort Sea. Prog Oceanogr 136:250–261
Gibbons JW, Scott DE, Ryan J, Buhlmann KA, Tuberville TD, Metts BS, Greene JL, Mills T, Leiden Y, Poppy S, Winne CT (2000) The global declines of reptiles, Déjà vu amphibians. Bioscience 50:653–666
Gilyazov A, Sparks TH (2002) Change in the timing of migration of common birds at the Lapland nature reserve (Kola Peninsula, Russia) during 1931–1999. Avian Ecol Behav 8:35–47
Gordo O, Brotons L, Ferrer X, Comas P (2005) Do changes in climate patterns in wintering areas affects the timing of the spring arrival of trans–Saharan migrant birds? Glob Change Biol 11:12–21
Gregory RD, Willis SG, Jiguet F, Voísek P, Klvanová A, van Strien A, Huntley B, Collingham YC, Couvet D, Green RE (2009) An indicator of the impact of climate change on European bird populations. PLoS ONE 4(3): e4678
Guo D, Desmet PG, Powrie LW (2017) Impacts of the future changing climate on the southern African biomes and the importance of geology. J Geosci Environ Prot 5:1–9
Harper EB, Rittenhouse TAG, Semlitsch RD (2008) Demographic consequences of terrestrial habitat loss for pool–breeding amphibians: predicting extinction risks associated with inadequate size of buffer zones. Conserv Biol 22:1205–1215
Harris JBC, Sekercioglu CH, Sodhi NS, Fordham DA, Paton DC, Brook BW (2011) The tropical frontier in avian climate impact research. Ibis 153:877–882
Hayes TB, Falso P, Gallipeau S, Stice M (2010) The cause of global amphibian declines: a developmental endocrinologist's perspective. J Exp Biol 213:921–933
Hayhoe K, Wake C, Huntington TG, Luo L, Schwartz MD, Sheffield J, Wood E, Anderson B, Bradbury J, Troy TJ, Wolfe D (2007) Past and future changes in climate and hydrological indicators in the US Northeast. Clim Dyn 28:381–340
Hetem RH, Fuller A, Maloney SK, Mitchell D (2014) Response of large mammals to climate change. Temperature 1(2):115–127
Hilbert DW, Bradford M, Parker T, Westcott DA (2004) Golden bowerbird (*Prionodura newtonia*) habitat in past, present and future climates; highlands due to global warming. Biol Cons 116:367–377
Hof C, Araujo MB, Jetz W, Rahbek C (2011) Additive threats from pathogens, climate and land use change for global amphibian diversity. Nature 480(7378):516–519
Hoffmann M, Hiltopn-Taylor C, Angulo A, Bohm M, Brooks TM, Butchart SHM, Carpenter KE, Chanson J, Collen BM, Cox NA et al (2010) The impact of conservation on the status of the world's vertebrates. Science 330:1503–1509
Huang SP, Chiou CR, Lin TE, Tu MC, Lin CC, Porter WP (2013) Future advantages in energetics, activity time and habitats predicated in a high–altitude pit viper with climate warming. Func Ecol 27:446–458
Huey RB, Deutsch CA, Tewksburry JJ, Vitt LJ, Hertz PE, Garland T Jr (2009) Why tropical forest lizards are vulnerable to climate warming. Proc Roy Soc Lond. B Biol Sci 276:1939–1948
Hughes AC, Lechner AM, Chitov A, Horstmann A et al (2020) Horizon scan of the belt and road initiative. Trends Ecol Evol 35(7). http://doi.org/10.1016/j.tree.2020.02.005

Huntington HP, Quakenbush LT, Nelson M (2016) Effects of changing sea ice on marine mammals and subsistence hunters in northern Alaska from traditional knowledge interviews. Biol Lett 12:20160198

Huppop O, Huppop K (2003) North Atlantic oscillation and timing of spring migration in birds. Proc Roy Soc Lond B 270:233–240

Hussain J, Zhou K, Guo S, Khan A (2020) Investment risk and natural resource potential in "Belt and Road Initiative" countries: a multi criteria decision–making approach. Sci Total Environ 723:137981

Inouye DW, Barr B, Armitage KB, Inouye BD (2000) Climate change is affecting altitudinal migrants and hibernating species. Proc Nat Acad Sci U S A 97:1630–1633

IUCN (2008) IUCN red list reveals world's mammals in crisis. Web Accessed on 12 Dec 2020 at https://www.iucn.org/content/iucn-red-list-reveals-world-mammals-crisis

IUCN (2018) The International Union for Conservation of Nature red list of threatened species. https://www.iucnredlist.org

Jankowski JE, Robinson SK, Levey DJ (2010) Squeezed at the top: interspecific aggression may constrain elevational ranges in tropical birds. Ecology 91:1877–1884

Jones PD, Osborn TJ, Briffa KR (2001) The evolution of climate over the last millennium. Science 292:662–662

Kerr J, Packer L (1998) The impact of climate change on mammal diversity in Canada. Environ Monit Assess 49:263–270

Khan H, Baig SU (2020) Biodiversity conservation in the Hindu Kush–Karakoram-Himalayan mountain region of northern Pakistan: overview of big mammal protection. J Mt Sci 17(6):1360–1373

Klemens MW, Thorbjarnarson JB (1995) Reptiles as a food resource. Biodivers Conserv 4:281–298

Knapp AK, Beier C, Aimee DDB, Classen T, Luo Y, Reichstein M, Smith MD, Smith SD, Bell JE, Fay PA, Heisler JL, Leavitt SW, Sherry R, Smith B, Weng E (2008) Consequences of more extreme precipitation regimes for terrestrial ecosystems. Bioscience 58:811–821

Lafferty KD (2009) The ecology of climate change and infectious diseases. Ecology 90:888–900

Laidre KL, Stern H, Kovacs KM, Lowry L, Moore SE, Regehr EV, Ferguson SH, Wiig O, Boveng P, Angliss RP, Born EW, Litvovka D, Quakenbush L, Lydersen C, Vonggraven D, Ugarte F (2015) Artic marine mammal population status, sea ice habitat loss and conservation recommendations for the 21st century. Conserv Biol 29:724–737

Lashari AK, Li W, Hassan M, Nabi G, Maybe PT, Islam MM, Rind KH, Ujjan SA (2020) Biodiversity conservation in China-Pakistan economic corridor region with strategic environmental assessment. Environ Sci Pollut Res 27:33500–33502

LaSorte FA, Jetz W (2010) Avian distributions under climate change: towards improved projections. J Exp Biol 213:862–869

Laurance WF (2008) Global warming and amphibian extinctions in eastern Australia. Aust Ecol 33:1–9

Lawler JJ, Shafer SL, Bancroft BA, Blaustein AR (2009) Projected climate impacts for amphibians of the Western Hemisphere. Conserv Biol 24:38–50

Lebreton J-D (2011) The impact of global change on terrestrial vertebrates. CR Biol 334:360–369

Lee TD, Barreett JP, Hartman B (2005) Elevation, substrate and the potential for climate –induced tree migration in the White Mountains, New Hampshire, USA. For Ecol Manage 212:75–91

Leech DI, Crick HQP, Rehfisch MM (2004) The effect of climate change on bird species in UK. British Trust for Ornithology research report 369

Lehikoinen E, Sparks T (2010) Changes in migration. In: Moller AP, Fiedler W, Berthold P (eds) Effects of climate change on birds, 1st edn. Oxford University Press, Oxford, pp 89–112

Lehikonen E, Sparks TH, Zalakevicius M (2004) Arrival and departure dates. Adv Ecol Res 35:1–31

Lemes P, Loyola RD (2013) Accommodating species climate–forced dispersal and uncertainties in spatial conservation planning. PLoS ONE 8:e5432

Levinsky I, Skov F, Svenning J-C, Rahbek C (2007) Potential impact of climate change on the distribution and diversity patterns of European mammals. Biodivers Conserv 16:3803–3816

Lister AM, Stuart AJ (2008) The impact of climate change on large mammal distribution and extinction: evidence from last glacial/interglacial transition. C.R. Geoscience 340:615–620
Loarie SR, Duffy PB, Hamilton H, Asner GP, Field CB, Ackerly DD (2009) The velocity of climate change. Nature 462:1052–1055
Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. Science 333:616–620
Loss SR, Terwillger LA, Peterson AC (2011) Assisted colonization: integrating conservation strategies in the face of climate change. Biol Cons 144:92–100
Lourenco-de-Moraes R, Landsac-Toha FM, Schwind LTE, Arrieira RL, Rosa RR, Terribile LC, Lemes P, Rangel RF, Diniz-Filho JAF, Bastos RP, Baily D (2019) Climate change will decrease the range size of snake species under negligible protection in the Brazilian Atlantic forest hotspot. Sci Rep 9L:8523
Lovejoy T (2008) Climate change and biodiversity. Rev Sci Tech 27:331–338
Lukoschek V, Beger M, Ceccardelli D, Richards Z, Pratchett M (2013) Enigmatic declines of Australia's sea snakes from a biodiversity hotspot. Biol Cons 166:191–202
Marchant JH, Freeman SN, Crick HQP, Beaven LP (2004) The BTO Heroines Census of England and Wales 1928–1998: new indices and a comparison of analytical methods. Ibis 146:323–334
Marini MA, Barbet-Massin M, Lopes LE, Jiquet F (2009) Major current and future gaps of Brazilian reserves to protect Neotropical savanna birds. Biol Cons 142:3039–3050
Matata DJ, Adan A (2018) Causes of climate change and its impacts in the multi-sectoral areas in Africa—need for enhanced adaptation policies. Curr J Appl Sci Technol 27:1–10
Mckelvey KS, Copeland JP, Schwartz MK, Littell JS, Aubry KB, Squires JR, Parks SA, Elsner MM, Mauger GS (2011) Climate change predicted to shift wolverine distributions, connectivity and dispersal corridors. Ecol Appl 21:2882–2897
McKinny ML (2008) Effects of urbanization on species richness: a review of plant and animals. Urban Ecosyst 11:161–176
Milanovich JR, Peterman WE, Nibbelink NP, Maerz JC (2010) Predicted loss of salamander diversity hotspot as a consequence of projected global climate change. PLoS ONE 5(8):1–10
Mokhatla MM, Rodder D, Measey GJ (2015) Assessing the effects of climate change on distributions of Cape Floristic region amphibians. S Afr J Sci 111(11/12):1–7
Monasterio C, Shoo LP, Salvador A, Iraeta P, Diaz J (2013) High temperature constrains reproductive success in a temperate lizard: implications for distribution range limits and the impacts of climate change. J Zool 291:136–145
Moore SE, Huntington HP (2008) Artic marine mammals and climate change: impacts and resilience. Ecol Appl 18:S157–S165
Moore FC, Lobell DB (2015) The fingerprint of climate trends on European crop yields. Proc Nat Acad Sci 112:2670–2675
Morelli TL, Maher SP, Lim MCW, Kastely C, Eastman LM, Flint LE, Flint AL, Beissinger SR, Moritz C (2017) Climate change refugia and habitat connectivity promote species persistence. Clim Change Responses 4:1–12
Moreno-Rueda G, Pleguezuelos JM, Pizzarro M, Montori A (2011) Northward shifts of the distribution of Spanish reptiles in association with climate change. Conserv Biol 26:278–283
Munguia M, Rahbek C, Rangel TF, Diniz-Filho JAF, Araujo MB (2012) Equilibrium of global amphibian species distribution with climate. PLoS ONE 7(4):e34420
Nagy LR, Holmes RT (2005) Food limits annual fecundity of a migratory songbird: an experimental study. Ecology 86:675–681
Neelin JD, Chou C, Su H (2003) Tropical drought regions in global warming and El Nino teleconnections. Geophys Res Lett 30:2275
Newbold TAS (2005) Desert horned lizard (*Phrynosoma platyrhinos*) locomotor performance: the influence of cheatgrass (*Bromus tectorum*). Southwestern Nat 50:17–23
Newbold T (2018) Future effects of climate and land use change on terrestrial vertebrate community diversity under different scenarios. Proc Roy Soc B Biol Sci 285:20180792

Niven DK, Butcher GS, Bancroft GT (2009) Birds and climate change: ecological disruption in motion. National Audubon Society, New York, NY

Ochoa-Ochoa LM, Rodriguez P, Mora F, Flores-Villela O, Whittaker RJ (2012) Climate change and amphibian diversity pattern in Mexico. Biol Cons 150(1):94–102

Pacifici M, Foden WB, Visconti P, Watson EM, Butchart HM, Kovacs KM et al (2015) Assessing species vulnerability to climate change. Nat Clim Change 5:215–225

Parmesan C (2006) Ecological and evolutionary responses to recent climate change. Annu Rev Ecol Evol Syst 37:637–889

Pautaso M, Dehnen-Schmutz K, Holdenrieder O, Pietravalle S, Salama N, Jeger MJ, Lange E, Hehl-Lange S (2010) Plant health and global climate change—some implications for landscape management. Biol Rev 85:729–775

Pearson RG, Dawson TP (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Glob Ecol Biogeogr 12:361–371

Pimm SL, Jenkins CN, Abell R, Brools TM, Gittleman JL, Joppa LN, Raven PH, Roberts CM, Sexton JO (2014) The biodiversity of species and their rates of extinction, distribution and protection. Science 344:1236752–1246752

Poloczanska ES, Burrows MT, Brown CJ, Molinos JG, Halpern BS, Hoegh-Gulberg O, Kappel CV, Moore PJ, Schoeman DS, Sydeman WJ (2016) Response of marine organisms to climate change across oceans. Front Mar Sci 3:62

Pomara LY, Ledee OE, Matin KJ, Zuckerberg B (2014) Demographic consequences of climate change and land cover help explain a history of extirpations and range contraction in declining snake species. Glob Change Biol 20:2087–2099

Preston K, Rotenberry JT, Redak RA, Allen MF (2008) Habitat shifts of endangered species under altered climate conditions: importance of biotic interactions. Glob Change Biol 14:2501–2515

Przybylo R, Shelton BC, Merlia J (2000) Climate effects on breeding and morphology: evidence for phenotypic plasticity. J Anim Ecol 69:395–403

Rajpar MN, Zakaria M (2011) Bird species abundance and their correlationship with microclimate and habitat variables at natural wetland reserve, Peninsular Malaysia. Int J Zool 758573:1–17

Reale D, McAdam AG, Boutin S, Berteaux D (2003) Genetic and plastic responses of a northern mammal to climate change. Proc R Soc Lond B 270:591–596

Redford KH, Ray JC, Boitani L (2011) Mapping and navigating mammalian conservation: from analysis to action. Philos Trans R Soc Lond B Biol Sci 366(1578):2712–2721

Reed M, Stringer LC (2015) Climate change and desertification: anticipating, assessing and adapting to future change in drylands. In: Impulse report for 3rd UNCCD scientific conference, Agropolis International, Montpellier, France, pp 1–140

Ripple WJ, Painter LE, Beschta RL, Gates CC (2010) Wolves, elk, bison and secondary trophic cascades in Yellowstone National Park. Open Ecol J 3:31–37

Rivalan P, Frederiksen M, Lois G, Julliard R (2007) Contrasting responses of migration strategies in two European thrushes to climate change. Glob Change Biol 13:275–285

Rodenhouse NL, Mattews SN, McFarland KP, Lambert JD, Iverson LR, Sillett TS, Holmes RT (2008) Potential effects of climate change on birds of the Northeast. Mitig Adapt Strat Glob Change 13:517–540

Rodenhouse NL, Chrstenson LM, Parry D, Green LE (2009) Climate change effects on native fauna of northeastern forests. Can J for 39:249–263

Roelants K, Gower DJ, Wilkinson M, Loader SP, Biju SD, Guillaume K, Moraiu L, Bossuyt F (2007) Global patterns of diversification in the history of modern amphibians. Proc Nat Acad U S A 104:887–892

Rosenzweig C, Neofotis P (2013) Detection and attribution of anthropogenic climate change impacts. Wires Clim Change 4:121–150

Saenz D, Fitzgerald LA, Baum KA, Conner RN (2006) Abiotic correlates of anuran calling phenology: the importance of rain, temperature, and season. Herpetol Monogr 20(1):64–82

Sarmento Cabral J, Jeltsch F, Thuiller W, Higgins S, Midgley GF, Rebelo AG, Rouget M, Schurr FM (2013) Impacts of past habitat loss and future climate change on the range dynamics of South African Proteaceae. Divers Distrib 19(4):363–376

Scheidel A, Neofotis P (2013) Detection and attribution of anthropogenic climate change impacts. Wiley Interdisc Rev Change 4:121–150

Scheidel A, Work C (2018) Forest plantations and climate change disorders: new powers of "green" grabbing in Cambodia. Land Use Policy 77:9–18

Schneider N, Griesser M (2009) Influence and value of different water regimes on avian species richness in arid inland Australia. Biodivers Conserv 18:457–471

Schumann N, Gales NJ, Harcourt RG, Arnould JPY (2013) Impacts of climate change on Australian marine mammals. Aust J Zool 61:146–159

Seavy NE, Humple DL, Cormier RL, Porzig EL, Gardali T (2018) Evidence of the effects of climate change on landbirds in western North America: a review and recommendations for future research in trends and traditions: avifaunal change in western North America. In: Shuford WD, Gill Jr RE, Handel CM (eds) Studies of western birds 3. Western field ornithologists, Camarillo, CA, pp 331–343. https://doi.org/10.21199/SWB3.18

Sekerioglu CH (2007) Conservation ecology: area trumps mobility in fragment bird extinctions. Curr Biol 17:R283–R286

Sekercioglu CH, Schneider SH, Fay JP, Loarie SR (2008) Climate change, elevational range shifts and bird extinctions. Conserv Biol 22:140–150

Sekercioglu CH, Primack RB, Wormworth J (2012) The effects of climate change on tropical birds. Biol Cons 148:1–18

Sekercioglu CH, Loarie SR, Brenes FO, Ehrlich PR, Daily GC (2007) Persistence of forest birds in the Costa Rican agricultural countryside. Conserv Biol 21(2):482–494

Sheriff MJ, Krebs CJ, Boonstra R (2009) The sensitive hare: sublethal effects of predator stress on reproduction in snowshoe hares. J Anim Ecol 78:1249–1258

Sillett TS, Holmes RT (2002) Variation in survivorship of a migratory songbird throughout its annual cycle. J Anim Ecol 71:296–308

Sinervo B, Mendez-de-la-Cruz F, Miles DB, Heulin B, Bastiaans E, Cruz MV-S, Lara-Resendiz R, Martinez-Mendez N, Calderon-Lazaro RN, Gadsden H, Avila LJ, Morando M, De la Riva I, Sepulveda PV, Rocha CFD, Ibarguengoytia N, Puntriano CA, Nassot M, Lepetz V, Oksanen TA, Chapple DG, Bauer AM, Branch WR, Clobert J, Sites Jr JW (2010) Erosion of lizard diversity by climate change and altered thermal niches. Science 329(5980):894–899

Sintayehu DJ (2018) Impacts of climate change on biodiversity and associated key ecosystem services in Africa: a systematic review. Ecosyst Health Sustain 4(9):225–239

Sommer JH, Kreft H, Kier G, Jetz W, Mutke J, Barthlott W (2010) Projected impacts of climate change on regional capacities for global plant species richness. Proc Roy Soc Lond B 277:2271–2280

Sonwa DJ, Dieye A, Mzouri EH, Majule A, Mugabe FT, Omolo N, Wouapi H, Bando JO, Brooks N (2017) Drivers of climate risk in African agriculture. Clim Dev 9:383–398

Sparks TH, Mason CF (2001) Dates of arrivals and departures of spring migrant take from the Essex Bird reports 1950–1998. Essex Bird report 1999, pp 154–164

Stuart S, Chason J, Cox N, Young B, Rodrigues A, Fischman D, Waller R (2004) Status and trends of amphibians declines and extinctions worldwide. Science 306:1783–1786

Surasinghe T (2010) The effects of climate change on global wildlife and terrestrial ecosystems. Taprobanica 2(1):30–47

Traill LW, Bradshaw CJA, Delean S, Brook BW (2010) Wetland conservation and sustainable use under global change: a tropical Australian case study using magpie geese source. Ecography 33:818–825

Valiela I, Bowen JL (2003) Shift in winter distribution in birds: effects of global warming. Ambio 32:476–480

Vie J-C, Hilton-Taylor C, Sturat SN (eds) (2009) Wildlife in a changing world—an analysis of the 2008 IUCN red list of threatened species. IUCN, Gland, Switzerland, p 180

Visser ME, Van Noordwijik AJ, Tinbergen JM, Lessells CM (1998) Warmer springs lead to mistimed reproduction in great tit (Parus major). Proc Roy Soc Lond Bull 265:1867–1870

Visser ME, Perdec AC, van Balen JH, Both C (2009) Climate change leads to decreasing bird migration distances. Glob Change Biol 15:1859–1865

Wake DB (2007) Climate change implicated in amphibian and Lizard declines. PNAS 104:8201–8202

Wake DB, Verdenburg VT (2008) Are we in the midst of the sixth mass extinction? A view from the world amphibians. Proc Natl Acad Sci U S A 105:11466–11473

Walsh H, Richardson DE, Marancik KE, Hare JA (2015) Long-term changes in the distribution of larva and adult fish in the northeast US shelf ecosystem. PLoS ONE 10:e0137382

Walther G-R (2010) Community and ecosystem responses to recent climate change. Philos Trans Roy Soc B 365:2019–2024

Wanless S, Frederiksen M, Walton J, Harris MP (2009) Long term changes in breeding phenology at two seabird colonies in the western North Sea. Ibis 151:274–285

Waycott M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarink S, Calladine A, Fourqurean JW, Heck KL, Hughes AR, Kendrick GA, Kenworthy WJ, Short FT, Williams SL (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci U S A 106:12377–12381

Weathers WW, Hodum PJ, Blakesley JA (2001) Thermal ecology and ecological energetics of California spotted owls. Condor 103:678–690

Webb JK, Pike DA, Shine R (2008) Population ecology of the velvet gecko Oedura lesurii in south eastern Australia: implications for the persistence of an endangered snake. Aust Ecol 33:839–847

Witczak L, Dorcas M (2009) What are frogs and snake's worth? The economic value of reptiles and amphibians inhabiting the Charlotte-Metropolitan area of North Carolina. J N C Acad Sci 125(4):131–137

Zani PA, Rollyson M (2011) The effects of climate modes on growing season length and timing of reproduction in the Pacific Northwest as revealed by biophysical modeling of lizards. Am Midl Nat 165:372–388

Zhang M-G, Zhou Z-K, Chen W-Y, Silk JWF, Cannon CH, Raes N (2012) Using species distribution modelling to improve conservation and land use planning of Yunnan, China. Biol Conserv 153:257–264

Zong L, Wang (2017) Evaluation on effect of land consolidation on habitat quality based on InVEST model. Trans Chin Soc Agric Eng 33:250–255

Dr. Rajpar is an Assistant Professor of Forestry and Wildlife Ecology at the Department of Forestry, Faculty of Life Sciences, Shaheed Benazir Bhutto University Sheringal Dir Upper, Khyber Pakhtunkhwa, Pakistan. He is recognized as a one of the leading Wildlife Ecologist in Pakistan. He is a Regional Fellow in the International Ornithologist Union. He has extensive academic and research experience in the field of wildlife and forest ecology, conservation and management, especially endangered and threatened species. He has published many research papers in scientific journals and proceedings, book chapters, and a book. He has carried out eight research projects on various aspects of wildlife ecology and conservation. Currently, he is engaged to ascertain the impacts of climate change, food resources, micro-climate, habitat characteristics and alteration, water level fluctuations and human disturbance on the population structure of wildlife species, particularly threatened and endangered species.

Dr. Michael R. Reed is an emeritus professor of Agricultural Economics at the University of Kentucky, USA. He holds a Ph.D. in economics from Iowa State University (1979); a Doctor Honoris Causa (Honorary Ph.D.) from Bucharest University of Agricultural Sciences and Veterinary Medicine (Romania); and an Honorary Ph.D. from the Faculty of Business Administration, Maejo University (Thailand).

His principal area of research is international trade in agricultural products, including the effects of macroeconomic policies and exchange rates on US food exports, international commodity price dynamics, consumer demand in various countries, and the effects of competition patterns on world agricultural trade pattern

Climate Change and Disappearing Habitats: The Case of Majuli Island in Northeast India

Nira Ramachandran

Abstract Majuli, the world's largest riverine island with a history of occupation dating back to 1228 CE, is now faced with the threat of imminent extinction. Informed opinion states that the island may well be submerged within the next two decades. Located in the Brahmaputra river basin in the state of Assam, India, Majuli has always been prone to seasonal flooding and erosion, but climate change-induced impacts have speeded up the process. While adaptation to annual monsoon flooding and flood-created losses is an inextricable part of the lives of the Mishing tribe, the original inhabitants of the island, they are helpless in the face of the massive soil erosion, which now destroys the island, sweeping away crops, livestock, and entire villages into the waters. From the 1960s onwards, over half the 210 cadastral villages on the island have partly or fully been lost to the floods. The rapidly changing and volatile climate, unwittingly augmented by well-meant but misguided developmental interventions, has led to increasing tension and even conflict between the inhabitants and officials. Additionally, the island, home to a rich biodiversity, faces the onslaught of wild animals in search of food and shelter as their own habitats shrink. Man–animal conflict is thus also on the rise. With the loss of their homes and lands, the only option for this subsistence agricultural community is to move to refugee camps, squatter settlements, or to mainland towns to earn a livelihood for which they are ill prepared. Majuli is a prime example of the need for localizing climate mitigation and adaptation processes and provides a formidable challenge if this is to be accomplished in time to save this unique natural and cultural habitat.

Keywords Biodiversity · Climate change impacts · Conflicts · Habitats · Majuli Island

N. Ramachandran (✉)
Gurgaon, India
e-mail: nira_ramachandran@hotmail.com

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_5

1 Background

Climate change is now widely accepted as a growing cause of impoverishment and displacement. Kalin (2010) writes that in 2008, of the 36 million people displaced by sudden onset disasters, 20 million were displaced by climate-related disasters as against 16 million by non-climate-related disasters (OCHA and IDMC and NRC 2009). Overall, the phenomenon of people displaced by the effects of climate change is highly complex and, in many ways, little understood (Castles 2010). However, "it is clear that global warming and the associated rise in sea levels, place the densely populated 'mega-deltas', especially in Asia and Africa, as well as small, low-lying islands all over the world at the greatest risk from floods, storms, salinisation of groundwater and soils, coastal flooding and eventual submergence" (IPCC 2007).

This seems to be the case with Majuli Island in the state of Assam. The island owes its origin to the frequent earthquakes occurring in the Northeastern states of India, which have changed the course of the Brahmaputra river and its tributaries over the centuries, eventually resulting in a massive elongated island (Down to Earth 2016), which once (Area first recorded in 1901) covered over 1326 km^2 (Nayak and Das 2008), but is now reduced to a mere 584 km^2 (Census 2011).[1] Extending over a length of 80 km with a width of 10–15 km, Majuli is surrounded by a number of small islets or *chaporis* created by the braiding rivers; some of these are inhabited and are also the parts of Majuli Island, which are most affected by flooding and erosion (GoA 2014). The island is enclosed on the North by the river Luhit, which branches off from the Brahmaputra, flowing north for almost 100 km, before rejoining it near Golaghat district. Majuli stands a mere 85–90 m above mean sea level. Endowed with fertile soils, rich biodiversity, a mix of tribal and non-tribal populations, it also is home to a number of *satra*s (monasteries) preserving the Vaishnavite culture and artefacts of the region, which make it an important pilgrimage destination. Majuli Island was declared a Cultural Heritage Site by the State Government of Assam in 2006 and is awaiting recognition from UNESCO as a World Heritage site. For long, a part of Jorhat district, in 2016, Majuli was accorded the status of an independent district (Fig. 1).

The state of Assam is prone to a regular monsoon-related flooding, and Majuli Island located in the midst of the largest and most turbulent river of the subcontinent is particularly vulnerable to the twin threats of flooding and soil erosion. The changing climate of the region, with sharp increases in summer temperatures, unpredictable rainfall patterns, and, consequently, peak flows in the river, is further exacerbating the situation. The State Action Plan for Climate Change (Government of Assam, Department of Environment 2015) states that the annual mean temperature in the state has increased by 0.59 °C over the last 60 years (1951–2010) and is likely to increase by 1.7–2.2 °C by 2050. Climate projections in this plan also predict that extreme rainfall events will increase by 38%. In this context, it is likely that Majuli will continue to face the existing climate-related threats in the future and, perhaps, exacerbated impacts.

[1] Various figures are quoted by different authorities regarding the current size of the island.

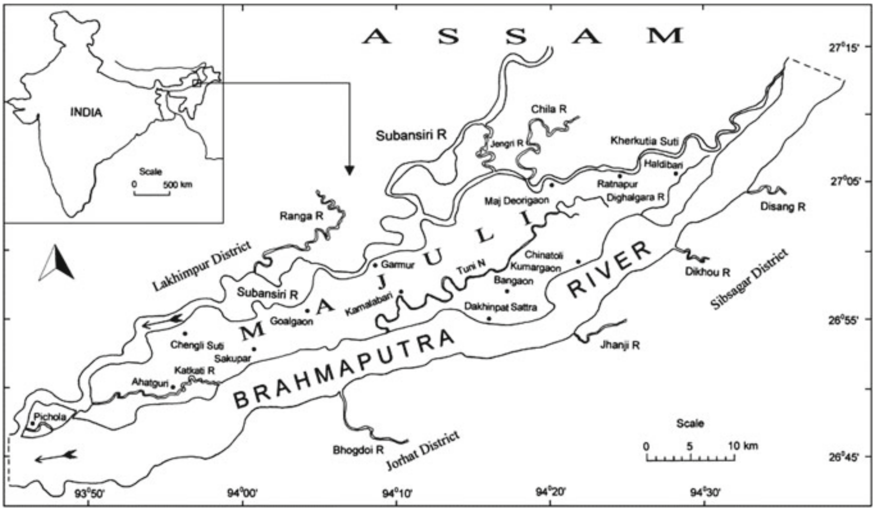


Fig. 1 Majuli Island. *Source* Sarma and Phukan (2003)

2 The Island and the People

The island is home to an estimated 174,063 people (2018–19, GoA, Agriculture Dept.)—a growth of 4% over the 167,304 recorded in census 2011—living in 248 villages, of which 33 are non-cadastral (which do not have revenue maps), mostly those located on the *chaporis*. The majority of the population (70%) is engaged in subsistence farming, with a small percentage working as agricultural labour. The agricultural labourers belong to households, which have lost their own lands to flood erosion, and can no longer be rehabilitated on the island because of shortage of available land. Their arrangement to work for landowners is usually based on a fifty–fifty division of the produce from the land, which gives them a livelihood, but a precarious one as it is based on an informal arrangement which can be revoked at any time (Sahay and Roy 2017).

In addition to the devastating impacts of climate change, large dams constructed upstream restrict the flow of the river, making the floods even more unpredictable. A vicious cycle of erosion and destruction of arable land, leading to increasing deforestation to regain cultivable land and, in turn, increasing soil erosion, has been set in motion (Roychoudhary 2017). The increased deposition of silt additionally raises the level of the riverbed making it too shallow to contain the floodwaters.

The island has two broad physiographic divisions: the outer region consisting of the land outside the embankments and the smaller islands or *chaporis*. This low-lying area is extremely flood prone with sandy soils given over to the winter cultivation of pulses, mustard, and vegetables, once the waters recede. It is also home to most of the tribal population. The inner region is more fertile with black silt deposits

Table 1 Majuli: land use in hectares (2010)

Type of land use	Area in hectares	% to total area
Woodland	3575.97	6.551281
Grasslands	18,835.5	34.50718
Non-Forest/Agricultural Land	23,674.3	43.372
Water	3575.97	6.551281
Sandbar	4922.55	9.018254
Total	54,584.29	

Source Sahariah et al. (2013)

and contains the major cultivated area. The monasteries, the villages, administrative offices, and schools are all located in this part (Kalita 2016) (Table 1).

Agricultural land, the major land-use type in Majuli, accounts for 43% of the total area. Another 35% is under grasslands. Forests cover about 7%, while the remaining 16% is under water and sandbars. There are two main cropping seasons—summer and winter for the staple crop paddy, while cash crops like pulses and oilseeds are grown in the autumn. Pastures support the large livestock population. While tractors, improved seed, pesticides, and fertilizers are now being used by some of the farmers, usually under government schemes, the availability is limited and productivity has declined with many farmers being forced to migrate to earn a livelihood (Table 2).

Of the main workers, over 70% are farmers, with an additional 4% working as agricultural labour. Thus, almost three-quarters of the working population are engaged in agriculture. Workers in household industries account for only about 5% of the working population, indicating a sector which needs to be expanded to promote new livelihoods. Women form only about 30% of the total farmers and main workers, but in the case of agricultural labour, more than half (53%) are women. Fishing is an important source of income for over 80% of the households.

Table 2 Majuli: occupational structure (2011)

	Total	% to main workers	Male	Female	% female to total
Main workers	53,484		38,148	15,336	28.67
Cultivators	37,352	69.84	26,477	10,875	29.11
Agricultural labourers	1373	3.68	648	725	52.80
Workers in household industries	2598	4.8	1389	1209	46.53
Other workers	12,161	22.7	9634	2527	20.78
Marginal workers	31,389		11,221	20,168	64.25
Non-workers	82,431		36,197	46,234	56.09

Source Census of India (2011)

Table 3 Livestock population, 2020

Livestock	Population
Cattle	2,13,378
Buffaloes	42,043
Goats	47,727
Sheep	2131
Horses and ponies	543
Pigs	90,505
Ducks and poultry	3,36,318
Total livestock	7,32,645

Source: GoA, Animal Husbandry and Veterinary Department, 2020

Table 4 Food security, 2018–19

Crop	Requirement[2] (metric tonnes)	Production (metric tonnes)	Surplus (metric tonnes)
Rice	20,330.5	35,584	14,253.5
Pulses	3037	7839	4535
Oilseeds (mustard)	1778.9	1745.7	−33.15

Source GoA, Agriculture Department[3]

The island has a considerable livestock population with over 254,000 head of cattle and water buffaloes. Goats, pigs, and poultry are also reared in large numbers providing an additional source of food and cash income for the local farmers (Table 3).

Despite the annual ravages of crops, livestock, and land wreaked by flooding and erosion, the island remains remarkably self-sufficient in food production to date. Table 4 tabulates the requirement of the three staple food crops—rice, pulses, and oil—on the basis of the current population (2018–19). It is clear that the food security of the population is assured even without outside assistance.

Despite being a multi-ethnic society, Majuli is yet culturally homogeneous. Demographically, it is a mixture of different ethnic groups, such as the Assamese, Mishings, Kacharris, Deoris, and Nepalese, who have migrated to make their home on Majuli. Yet all of these groups have accepted the island's unique Vaishnavite culture and helped in its preservation, protection, and propagation (Sahay and Roy 2017). In keeping with the simple agrarian lifestyle on the island, which continues to follow the traditional pattern, Majuli is also renowned for its age-old monasteries or *satras*, which help in preserving the Vaishnavite culture and artefacts of Assam. Manuscripts, historical documents, and ancient coins (Sahariya et al. 2013) as well as crafts specific

[2] Requirement is calculated on the basis of the following formula: 400 gms of rice, 65 gms of pulses, and 4.35 gms of oilseeds per adult per day.

[3] Accessed at: https://majuli.gov.in/departments/agriculture.

to the island like mask making, boat making, exotic pottery, quilting (the famous ribbed quilt or *Jim*), and the Raas Leela dance form are all traditional parts of this culture. The 65 original monasteries have now been reduced to a mere 23 in number, after losing their land and buildings due to flooding and erosion. The larger ones with better financial status have relocated within the island, some like the Auniati *Satra* relocating as many as three times in the last fifty years, while others have moved off the Island itself. As Sahay and Roy (2017) write, “the closing down or relocation of *satras* off Majuli symbolizes not just the end of a *Satra* in Majuli, but the closure of a powerful institution of cultural continuity”.

3 The Issue

As mentioned above, recurrent flooding and the accompanying soil erosion are part of the life of the island residents, who resort to traditional knowledge and practices to cope with these annual events. Homes are built on stilts (*Chang Ghars*); when these are washed away or submerged, the residents move to the high embankments to sit out the fury of the flood, or to rafts made of banana trunks (*Bhur*), which are often used as temporary homes with living and cooking facilities. However, in recent years, while flooding is becoming more severe, the normal rich silt deposits, which rejuvenate the soil each year, are being replaced by sand and salt, which crust the soil, making it infertile. Rising summer temperatures are creating periods of drought in these rain fed farm areas and simultaneously leading to glacial melt in the upper reaches with increased flows downstream in the already turbulent river. Rainfall patterns are changing and becoming unpredictable, making it difficult for farmers to plan their sowing schedules.

Table 5 records the sharp rise in soil erosion from the early years of the twentieth century. It is immediately apparent that no change took place for over fifty years till the early seventies. For the next 25 years, there was a minor increase, but from 1996 onwards, the erosion rates escalated over fourfold.

Table 5 Average annual rate of erosion

Period	Eroded area per year (km^2)
1917–1972	1.77
1972–1996	1.84
1996–2001	6.42
2004	8.58
2008	– 4.16
2013	– 16.36

Source Sarma and Phukan (2003). Data for 2004–13 is based on satellite images (Sarma 2014)

Table 6 Reducing area of Majuli Island

Year	Area (km^2)
1901	1325.5
1941	1324.0
1972	564.01
1996	453.76
2001	421.65
2017	487.5
2020	423.0

Source Sarma and Phukan (2003). Data for 2017 is from Roy et al. (2020), and for 2020 from Satellite imagery (Saikya et al. 2020)

The result of this change in rates of erosion can be seen in Table 6 which documents the shrinking of the island during the same period. However, on a more positive note, the efforts of the Brahmaputra Board and the approval and implementation of the Majuli Protection from Floods and Erosion Scheme in 2004 appear to be having an impact, with the island regaining landmass at a rate of 2–2.5 km^2 annually (Kalita 2016).

To explain the intensity of the problem, flood damage in a single three-month monsoon season (June to September, 2012) is tabulated in Table 7. Over half the villages on the island were flood affected, with 11 villages being totally washed away. Almost the entire population was affected by the floods, with 146 houses being fully destroyed, and 11 being washed away. A major portion of the standing crops were destroyed, as were a large number of cattle, though loss of human lives was limited.

The floods of 2016 were no less severe. As Roychowdhury (2017) writes, a total crop area of 99,416.44 ha was destroyed in the floods that took place [in the Assam valley] during the monsoons of 2016 (Assam Tribune 2016). Apart from crops,

Table 7 Flood damage in 2012–13 (June to September)

Area affected	42.83 ha
No. of affected villages	127
Population affected	1,66,000
Total houses destroyed	157
Fully destroyed houses	146
Washed away	11
Value	INR 23,555,000
Lives lost	4
Cattle lost	138
Value	INR 20,70,000
Damage to crops	23,171.62 ha

Source GoA, Disaster Management Plan for Majuli (2014) there was enormous infrastructural damage. Houses, schools, embankments, roads, bridges, and power transmitters are destroyed each year. Vulnerability of people to water-borne and vector-borne diseases increase significantly. Living under these circumstances while bearing the costs of natural disasters year after year often compel people to look at migration as a feasible alternative.

A recent field study (Saikya et al. 2020) found that during the 2000–2020 period, the annual depositional rate (4.17 km^2) exceeded the erosion (2.1 km^2) rate, contributing to the creation of many new islands. Due to ongoing river erosion and deposition, the island area continues to change constantly. More than 50% of the respondents in the survey acknowledged an increased drought incidence and a threat to cultivation. The intensity of impact varies based on their location in high- or low-flood zones. Since the severity of flood, erosion, and landslides has not increased in the low-flood zones, fewer than 20% of respondents from these areas identified the current hazards as severe disasters. However, more than 80% of respondents from the high-flood zone reported significant damages in assets and crops. Overall, 93% of respondents from high-flood zones and 79% from low-flood zones claimed that the occurrence of extreme events had increased in the last five years.

The rising levels of the floodwaters are also adversely impacting the livelihoods of fisherfolk. As the river becomes wider and shallower, the waters become muddy and only small fish can be found. The larger fish migrate towards deeper waters in the vicinity of the Kaziranga National Park, where fishing is prohibited (David 2020).

4 Displacement

One of the drawbacks of living in a flood-prone area is displacement. The Assam Valley regularly faces flooding with low-lying villages being submerged for several weeks, or even months during the monsoons. The stranded villagers move to higher ground with their livestock, often to refugee camps to escape the fury of the floods. Once the waters recede, they return to their homes and resume their normal lifestyles. But in Majuli, the pattern is different. While flood-affected villagers do move to embankments, higher ground, or other districts as do those on the mainland, once the waters recede, the situation is different. The refugees from Majuli have no home or land or village to return to, as these are, all too often, swept away by the rising waters. For years now, the Sub-Divisional Relief Committee for Natural Disasters has been allocating land both on the island itself and in neighbouring mainland districts to the victims; but now these vacant lands have run out, and the people of Majuli have nowhere to go.

While some of the evacuees work as agricultural labour on the fields of large landowners on the island, others migrate to neighbouring towns to eke out a living as rickshaw pullers or cart pullers or take up other manual jobs. Of late, men have begun migrating to far off cities in states as far as Kerala and Andhra Pradesh (in South India) to take up semi-skilled jobs in factories or as watchmen, etc. In general, however, the people have strong links with their island home and do not easily accept relocation. David (2020) writes of men who quit their jobs and return to the island during the six-month-long flooding season to ensure the safety of their families and livestock. The attachment to their home is so strong that many islanders cannot dream of living elsewhere. She quotes Diganto, a villager on the island, who said: “This is my birthplace. All my ancestors were born here,” … “and even if I wanted to leave, there is no way I could. I don’t have the money to just walk into Jorhat town and buy a piece of land. I have to take all my struggles in stride and survive. This is my land, and I shall die here”.

At least 70 villages on Majuli have been decimated by erosion, and most of the villagers do not or cannot afford to leave the island. So, while the island is shrinking, the population either remains the same or increases (David 2020). Analysing population growth data from 1901 onwards and changing densities in Majuli, Nayak and Das (2008) conclude that “the increase in density post 1971 can only be attributed to natural increase in population in a progressively shrinking island as evident from diminution in land area every successive decade albeit at a pace lower than what had happened during 1951–1961 decade. Evidently, the increasing density of population in the island despite outmigration suggests tremendous redistribution of population within the island for those people who had no option but to remain in the island faced with loss of land, villages, houses, crops and turning into environmental refugees”.

5 Conflict

For several decades, tension between the tribal population and the development agencies has been simmering. While the Majulis are a peace-loving people, differences arose between their viewpoints and those of the government. The residents felt that the embankments, concrete hedgehogs, and other mechanisms put in place to control flooding and reduce soil erosion were in fact doing the reverse. Flooding was increasing, fields were covered by sandy deposits instead of fertile river silt, and erosion continued unchecked, perhaps, occurring at an even faster pace. Things came to a head when the construction of the Bogibeel Bridge less than 100 km upstream of Majuli was announced. The proposed bridge was a dual rail and road bridge with a span of 5 km. With a negative experience from the construction of three previous bridges across the Brahmaputra, which led to unprecedented flooding and erosion in the villages downstream, the project which should have been a welcome development for enhancing connectivity in the region was viewed with suspicion and fear. Protests by the locals, a number of NGOs, and the Mishing Student’s Union became vociferous demanding a pre-project environmental impact assessment, which was not conducted (Mahanta and Mahanta 2006). A local NGO, the Majuli Suraksha Parishad, was set to file a case against the authorities, but was unable to do so because of lack of evidence. With little support, the protests died down and the bridge was constructed and commissioned in 2016.

The State Government's Disaster Management Plan (2014: 9) accepts that "a severe flood can cause huge damage to many roads, bridges and culverts. Reconstruction of these flood-damaged structures takes years together for sanction of funds and implementation to be complete. Often it leads to huge discontent among people resulting in several law and order problems". People are also dissatisfied because government schemes distributing seeds, fertilizers, and pesticides are often cornered by the more influential families, leaving the poorest without any benefits at all.

A recent field survey (Ink 2019) reiterates the persistence of this discontent. The Brahmaputra Board, which is currently in charge of the Disaster Management Plan, is known for using cost-effective methods like geo-bags (sand filled bags of heavy fabric) to line the island's endangered shoreline. A stretch of 27 km has been protected so far. Twenty-two lakh geo-bags were requisitioned to be put in place by May 2019, providing stability to the easily erodible banks. Residents, however, are largely sceptical about the effectiveness of these measures. Experts suggest that a nature-based solution may be a better option for controlling bank erosion given that grand investments on flood-erosion measures in large-scale structures—like embankments, dykes, or sandbags—have failed over the years (D'Souza 2006).

Ink (2018) writes "A resident of Sumoimari Ghat, a village at high risk of flooding, expressed disapproval of the government's riverbank protection methods". "Every year the soil is getting less," he told me. "Porcupines are provided by [the] government, but every day the soil is getting less" (Name Withheld, interview by the author, Sumoimari Ghat, 10 August 2018). The discontent that simmers among the locals is related to the fact that the government is more open handed with such eco-protective measures than with individual restitution.

The state provides a compensation of INR 95,100 to every family losing one's home due to the floods, while farmers are supposed to receive INR 12,200 per hectare for desilting of farmland. A large proportion of the island's population depends on fishing for food and livelihoods. The state is supposed to provide compensation of INR 1500 per month during the three-month fish breeding season (April to July), as well as an additional grant to compensate for loss of work during the floods, but most fisherfolk are yet to receive it (David 2020).

6 Conflict with the Wild

Not only is Majuli facing stirrings of discontent and revolt against the administration, another type of conflict is also on the rise—that between humans and wild animals. In the recent past, large herds of wild elephants numbering 80–100 take refuge on the *chaporis*, destroying crops, houses, and even people. All attempts at chasing them back to their original habitats are to no avail, as these have been lost to flooding and erosion much as is the case with their human counterparts. As Hiten Bashiya (undated) writes, accounts point to two distant events—the construction of the Subansiri Dam damaging the lowland Subansiri Reserve Forest and the deforestation precipitated by the internal migration and encroachment during the Bodo insurgency of the 1990s—that pushed these hapless elephants into the river to be condemned to ‘homelessness’ and the hapless people on the Brahmaputra’s banks to bear the brunt of the resultant conflict.

In the last few years, elephant–human conflict has taken on a frightening severity. Majuli was not known as elephant habitat. The first elephant was recorded in 1997, and by 2003, they had increased to 20. After 2003, over 70 elephants appeared there, and, ever since, these elephants have been living on the river islands east of Kaziranga all the way to near Panidehing Bird Sanctuary in Sibsagar. They move between river islands, and the people who live in that area face the brunt of the resultant serious human–elephant conflict throughout the year—with crop loss, damage to houses, and property and human deaths. Elephants have also had to pay with their lives. If we look back, we can correlate the beginning of conflict in Majuli to the busiest time in construction of the Subansiri Dam in 2001–2003. Although we do not have radiotelemtery data, from our experience we can say that the disruption of natural corridors must have a good deal to do with the Majuli conflict. Now, the Brahmaputra river islands are also occupied by humans. Naturally then, if people live where elephants do, somewhere or the other conflict is inevitable. In this way, the Brahmaputra, which was once the realm of elephants where they foraged and roamed, has now become an arena of conflict (Baishya, undated).

Elephants are now a permanent feature of the island and the *chaporis*, and human–elephant conflict continues. However, during the floods, there are other types of wildlife, which threaten the peace of mind and the security of the residents. As Barua (2019) writes, snakes are ubiquitous during floods. Although not all snakes are venomous, the very sight of snakes roaming around creates a deep sense of unease, sleeplessness, and fear among people. With a couple of occasional deaths due to snake bites, this fear spreads like wildfire, at times causing more harm than good.

Sometimes, bigger animals, such as wild elephants and rhinos, also ended up in unusual habitats after escaping floods in Kaziranga. Again, these animals are highly stressed and unpredictable in such unnatural habitats, and the local people, too, are afraid with the sudden presence of such animals in their surroundings. Violent conflicts are imminent in such cases and understandably so.

7 Conclusion

It is known that climate change hits hardest the populations which depend on Nature for their livelihoods. Such people are also the ones living on the brink of poverty with few, if any, of the basic amenities that others take for granted. But even these harsh living conditions may no longer be available to them, as their habitats are systematically being destroyed through drought, floods, soil erosion, landslides, or rising sea levels. No geographic location is completely secure from the vagaries of climate change, but there are numerous well-defined fragile, high-risk areas across the world, standing on the verge of complete destruction. The river island of Majuli is one such microcosm.

When assessing the impacts of climate change, one often overlooks the fact that it is not Nature alone, fuelled by thoughtless human actions that is wreaking this havoc. It is also, in many cases, human interventions being made to resolve the problem, which further exacerbate the situation and heighten adverse impacts. The case of Majuli reiterates the fact that the destruction, devastation, and displacement caused by the vagaries of climate change are more often than not enhanced by the schemes put in place for reconstruction and rehabilitation, often inadvertently. Financial aid for disaster management tends to get diverted to those who have more influence but less need. Money is poured into flood- and erosion-control interventions, like the embankments, and concrete porcupines being set up in Majuli for the benefit of the community, but little reaches the individuals and families, who are facing destitution. Quite often, in the words of a resident, “All the money spent on flood protection is swept away by the floods, leaving the people in the same hazardous situation as before”.

While other island habitats may be facing similar impacts of climate change, the socio-economic characteristics specific to Majuli make it infeasible to seek a common solution to the problem. The preceding discussion highlighted issues specific to Majuli and its people, which must be prioritized when planning for mitigation and adaptation in an acceptable manner:

- The alienation of the inhabitants from mainstream development agencies indicates that a centralized approach to resolving problems is being adopted, rather than a local, people-centric one. It is only when the people are taken aboard from the initial planning stage, with involvement in implementation, monitoring and evaluation, that successful and sustainable adaptation can be achieved.
- While migration may be a preferred option in similar circumstances elsewhere in the country or the world, in the case of Majuli, it is clear that the people do not wish to leave their home island. Migration is an enforced choice, not a freely selected alternative. Nayak and Das (2008), in an analysis of demographic data, point to the fact that despite migration taking place, population densities on the island, particularly in areas above the floodline, are increasing, indicating that displacement is largely internal with increasing concentration in safer areas.
- Many of the respondents in the research referred to above are fearful of losing their traditional livelihoods of farming, fishing, and plying boats, with the modernization and new developments in the region. The authorities must ensure that alternative livelihoods are created, wherein the traditional skills of the islanders and the resources they command can provide them with more dependable livelihoods to which they have access throughout the year, instead of the seasonal income to which they are accustomed. Informed opinion suggests the promotion of eco-tourism, homestays, religious tourism, and the revival and the promotion of religious and cultural festivals.
- The age-old crafts specific to the tribal population of the island could be promoted, with the setting up of marketing agencies.

- Cottage industries, based on the wide range of horticultural products grown on the island with well-established marketing facilities, could be established.
- To reduce man–animal conflict, some of the *chaporis* could be reserved for elephants alone, with the planting of crops suitable for elephant fodder. A farmer from Jorhat[4] has been planting crops for elephants on 2000 ha from 2011 onwards, both to provide them sanctuary, and to prevent the destruction of his standing crops.
- The proposal to connect this hitherto, almost inaccessible island by a bridge to the mainland, threatens the livelihoods of boatmen who have been plying passengers and goods to and for generations. Alternative sources of income for them must be a part of the Bridge Development Plan.
- Last but, certainly, not least, every aspect of the plans and development scenarios put in place for Majuli must be monitored by a committee of planners, environmental experts, and a broad range of resident representatives cutting across class and community affiliations, to ensure that every plan belongs to all the people. Only then can the island survive.

References

Baishya H (undated). The river elephants. Accessed at: https://thebrahmaputra.in/pdf/wild/4.%20The%20River%20Elephants.pdf

Barua M (2019) Beyond the death toll: the everyday violence of Assam's floods. Accessed at https://www.indiawaterportal.org/articles/beyond-death-toll-everyday-violence-assams-floods

Castles S (2010) Afterword: what now? In: McAdam J (ed) Climate change and displacement multidisciplinary perspectives. Hart Publishing

Census of India (2011) Majuli. Accessed at Majuli Circle Population, Religion, Caste Jorhat district, Assam-Census India

D'Souza R (2006) Drowned and damned: Colonial capitalism and flood control in Eastern India. Oxford University Press, New York

David S (2020) Treacherous river: how the Brahmaputra is eroding away lives and livelihoods in Assam. Accessed at https://www.newslaundry.com/2020/12/16/treacherous-river-how-the-brahmaputra-is-eroding-away-lives-and-livelihoods-in-assam-2

Down to Earth (2016) Disappearing Majuli, India's first river island district. Accessed at https://www.downtoearth.org.in/news/environment/disappearing-majuli-india-s-first-river-island-district-54610

Government of Assam (GoA) (2014) Disaster management plan for Majuli sub-division. Accessed at http://jorhat.gov.in/images/FOrms/DM-majuli.pdf

Government of Assam, Department of Environment (2015) Assam state action plan for climate change (2015–2020). Accessed at http://www.indiaenvironmentportal.org.in/files/file/Final%20draft%20ASAPCC%20document.pdf

Ink K (2019) Reimagining a violent landscape: disaster, development, and cartographic imagination in the Brahmaputra River Valley. Accessed at https://minds.wisconsin.edu/bitstream/handle/1793/79643/Inks%20Kevin%202019.pdf?sequence=1&isAllowed=y

[4] See Jadav Payenge, farmer in Bashya, Hiten (undated) The River Elephants, https://thebrahmaputra.in/pdf/wild/4.%20The%20River%20Elephants.pdf.

IPCC (2007) Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pachauri RK, Reisinger A (eds) IPCC, Geneva, Switzerland, p 104

Kalin W (2010) Conceptualising climate-induced displacement. In: McAdam J (ed) Climate change and displacement multidisciplinary perspectives. Hart Publishing, pp 81–104

Kalita J (2016) Impact of flood and riverbank erosion in Majuli, Assam (India) and its restoration measures. Accessed at https://www.researchgate.net/publication/311351457URES

Mahanta C, Mahanta A (2006) Bridge over the Brahmaputra. EPW XLI(7):579–581. Accessed at https://conflicts.indiawaterportal.org/sites/conflicts.indiawaterportal.org/files/conflicts_brahmaputra.pdf

Nayak DK, Mayuri D (2008) An assessment of redistribution of population in Majuli Island due to river bank erosion. Accessed at https://iussp.org/sites/default/files/event_call_for_papers/iussp13.pdf

OCHA and IDMC/NRC (2009) Monitoring disaster displacement in the context of climate change. Accessed at http://www.internal-displacement.org/8025708F004BE3B1/(httpInfoFiles)/12E8C7224C2A6A9EC125763900315AD4/$file/monitoring-disasterdisplacement

Roy N, Pandey BW, Rani U (2020) Protecting the vanishing geo-cultural heritage of India: case study of Majuli Island in Assam. Int J Geoheritage Parks 8(1):18–30

Roychoudhury M (2017) Exploring the environment and migration nexus in the Brahmaputra. Tata Institute of Social Sciences, Sixth Critical Studies Conference, Accessed at http://www.mcrg.ac.in/6thCSC/6thCSC_Full_Papers/Murchana.pdf

Sahariah D, Singha K, Bora DK, Kundu S, Das T, Sen S, Das K, Mili B, Baruah J, Sarma K, Saikia M, Saikia A (2013) Majuli at the crossroads: a study of cultural geomorphology. Space Culture, India. Accessed at https://www.researchgate.net/publication/294118468_Majuli_at_the_Crossroads_A_Study_of_Cultural_Geomorphology

Sahay A, Roy N (2017) Shrinking space and expanding population: socioeconomic impacts of Majuli's changing geography. Focus Geogr. Accessed at http://www.focusongeography.org/publications/articles/majuli/index.html

Saikya P, Nath AJ, Kumar R, Singh PK, Pandey R (2020) Vulnerability to climate change among the inhabitants of Majuli Island. Working Paper 314, IRMA, Anand, Gujarat, Accessed at https://www.researchgate.net/publication/346997555_Vulnerability_to_Climate_Change_among_the_Inhabitants_of_Majuli_Island

Sarma A (2014) Landscape degradation of River Island Majuli, Assam (India) due to flood and erosion by river Brahmaputra and its restoration. J Med Bioeng 3(4):272–276

Sarma JN, Phukan MK (2003) Origin and some geomorphological changes of Majuli Island of the Brahmaputra River in Assam. Accessed at http://www.sciencedirect.com

Dr. Nira Ramachandran is currently an independent researcher and consultant based at Gurgaon, India. As ICSSR Senior Fellow at the Institute of Economic Growth, New Delhi, her research was centred on accelerating the improvement in nutrition outcomes, subsequently published as 'Persisting Undernutrition in India: Causes, Consequences and Possible Solutions' (Springer 2014). Her interest areas include food security, nutrition, gender, and environmental issues. She has provided consultancy to a number of international organizations, including the FAO, UN World Food Programme, UNICEF, and The World Bank. She holds a Ph.D. from the Jawaharlal Nehru University, Delhi and has also been trained abroad. She has worked at some of the leading universities and research institutions in India, including the Indian Institute of Management, Bangalore, Bangalore University, Delhi University and the LBS National Academy of Administration, Mussoorie, the premier training institute for the Indian Administrative Services, where she was Coordinator of the Centre for Sustainable Development. She has lectured extensively and conducted training programmes in the areas of food security, environmental sustainability, primary education, research methodology, and project management techniques. She has to her credit several papers in peer-reviewed journals as well as a number of books.

Impacts of Climate Change on Biodiversity in Pakistan: Current Challenges and Policy Recommendations

Maqsood Anwar, Muhammad Rais, Mirza Barjees Baig, and Mohamed Behnassi

Abstract Pakistan is located at the crossroads of three zoogeographic regions (Oriental, Palaearctic, and Ethiopian) with great altitudinal variation and diversity of ecological zones. The diversity of plant species, insects, terrestrial and freshwater invertebrate species, marine invertebrates, mammals, avian species, reptiles, amphibians, and marine and freshwater fish species is quite significant. This biodiversity is increasingly threatened by climatic changes. Therefore, in this chapter, we highlight recent trends in climate change at the global, regional, and local levels, along with an overview of possible impacts of such changes on different ecosystems and various components of biodiversity with special reference to Pakistan. We have also identified the gaps in existing institutional and policy mechanisms and proposed measures for the enhancement of biodiversity conservation in Pakistan. The latest rankings of Pakistan in terms of vulnerability to climate change are alarming. Pakistan launched the National Climate Change Policy in 2012, while the Biodiversity Action Plan was developed in 2000 and updated in 2015 as the National Biodiversity Strategy and Action Plan (NBSAP). These documents address the need and opportunity for mitigation and adaptation to climate change and conservation of biodiversity. Based on our analysis of these documents, we suggest designing and

M. Anwar (✉)
Faculty of Forestry, Range Management and Wildlife, Pir Mehr Ali Shah Arid Agriculture University Rawalpindi, Rawalpindi, Pakistan
e-mail: maqsoodanwar@uaar.edu.pk

M. Rais
Department of Wildlife Management, Pir Mehr Ali Shah Arid Agriculture University Rawalpindi, Rawalpindi, Pakistan
e-mail: sahil@uaar.edu.pk

M. B. Baig
Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riyadh, Kingdom of Saudi Arabia
e-mail: mbbaig@ksu.edu.sa

M. Behnassi
Senior Environmentalist Expert, Economic Social & Environmental Council (ESEC), Director, Center for Environment, Human Security and Governance (CERES), Rabat, Morocco
e-mail: behnassi@gmail.com

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_6

implementing a strong community awareness program along with capacity building of relevant departments; extending and managing the buffer zone and providing incentives to local communities living around protected areas; establishing corridors and maintaining connectivity with nature reserves in the mountainous areas; systematic afforestation and restoration of degraded ecosystems; and enhanced research on the response of different species of plants and animals to climate change. All this together can help improve the adaptive capacities of the communities and contribute to climate mitigation in addition to conserving biodiversity. It is necessary as well to consider the needs of different sectors—such as agriculture and resource extraction—and monitor policies that address climate change but could negatively impact biodiversity and local communities.

Keywords Biodiversity components · Ecosystem resilience · Extinction · Global warming · Mitigation · Policy tools · Protected areas

1 Introduction

Pakistan is located at 30.3753° N, 69.3451° E and covers a land area of 88.2 million hectares (Fig. 1). From the coast and delta of the Indus River, Pakistan extends about 1700 km northwards among the three great mountain Ranges of the Himalayas, Hindu Kush, and Karakoram. Many of the peaks of these mountains exceed 8000 m, including K-2 (8611 m) the second highest peak in the world. The coastline of Pakistan stretches about 1046 km with 22,820 km^2 of territorial waters and about 196,600 km^2 of an Exclusive Economic Zone in the Arabian Sea. Therefore, Pakistan possesses a wide diversity of biota due to its extensive range of geographical and climatic factors (GoP 2014). The annual rainfall is 125 mm in the southern plains and ranges from 500 to 875 mm in the northern plain regions. About 70% of the total precipitation occurs in July to September. Summer months in the Indus Plains and the Thar Desert are very hot with monthly mean maximum temperatures exceeding 40 °C, with temperature reaching up to 53 °C. In winter months, mean monthly temperature in the plains is as low as 2–5 °C and often falls below zero in mountainous areas (Baig et al. 2020).

The country hosts a wide variety of habitats and associated biodiversity resources (Anwar 1996). This spans the Arabian Sea coastal areas containing mangrove forests, through sandy deserts, low altitude scrub forests, vast irrigated plains, riverine forest tracts, and high-altitude mountain ranges to permanent snowfields in the northern mountain ranges. According to various classification systems, Pakistan includes examples of two of the world's eight bio-geographic realms (the Indo-Malayan and Palaearctic) and four of the world's ten biomes (desert, temperate grassland, tropical seasonal forest, and mountain) (GoP 2014).

Pakistan is situated at the crossroads of three zoogeographic regions: Oriental, Palaearctic, and Ethiopian region. Himalayan and Baluchistan uplands possess species of Palaearctic origin, and the Indus Plain, Thar Desert, and Himalayan

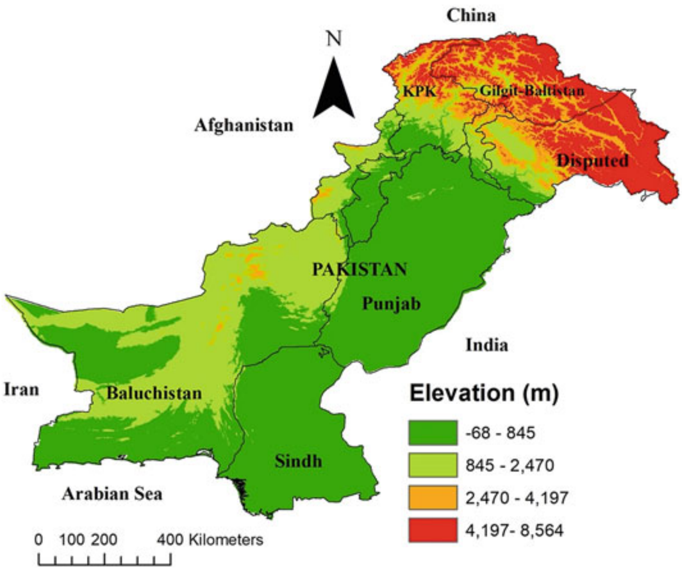


Fig. 1 Map of Pakistan showing elevation range

foothills have Oriental species, while Ethiopian species are distributed in dry south-western region along the Mekran coast (GoP 1992, 2000, 2009). Various classification schemes have been proposed. Mirza (1998) gave a comprehensive classification of ecozones based on amphibians, reptiles, birds, and mammals. The ecozones include barren highlands, alpine zone, dry temperate forest, moist temperate forest, sub-tropical pine forest, tropical deciduous forest, dry steppe forest, arid sub-tropical habitat, tropical thorn forest, and the Indus Basin. PARC (2019) identified ten agro-ecoregions based on physiographic, geology, climate, agriculture land, and water availability. These include Indus Delta, southern irrigated plains, sandy desert, northern irrigated plains, barren land, wet mountains, northern dry mountains, western dry mountains, dry western plateau, and Suleiman piedmont. Twelve zones were identified based on vegetation, including permanent snow fields and glaciers, dry alpine and cold desert zone, alpine scrub and moist alpine, Himalayan dry conifer forest, Himalayan moist temperate forest, sub-tropical pine forest, sub-tropical dry mixed deciduous scrub forest, Baluchistan Juniper and Pistachio scrub forest, dry sub-tropical, temperate semi-evergreen scrub forest, tropical thorn forest, sand dune desert, and mangrove and littoral zone (GoP 2000).

This chapter provides an overview of the biodiversity resources of Pakistan, along with an assessment of possible impacts of changes in the climatic patterns on different ecosystems and various components of its biodiversity. Gaps in existing institutional and policy mechanisms are identified, and measures for enhancing biodiversity conservation in Pakistan are proposed.

2 Biodiversity of Pakistan: An Overview

The great variation in the elevation and diversity of ecological zones is reflected in Pakistan's rich biodiversity. About 7000 plant species, 20,000 insect, terrestrial and freshwater invertebrate species, 700 marine invertebrates, 198 mammals, 690 avian species, 229 reptiles, 24 amphibians, and 1000 marine and 198 freshwater fish species have so far been documented from Pakistan (Table 1) (GoP 2014).

Pakistan is particularly rich in mammalian (198 species) and avian diversity (690 species). The mammals of Pakistan can be grouped as small-sized mammals (*Order Insectivora, Chiroptera, Pholidota, Lagomorpha, Rodentia*) (Fig. 3) and medium/large-sized mammals (*Primates, Carnivora, Artiodactyla, Perissodactyla, Cetacea*) (Figs. 2 and 3). The avifauna can be grouped as water birds (*Gaviiformes, Podicipediformes, Procellariiformes, Pelecaniformes, Ciconiiformes, Anseriformes,* and *Charadriiformes*) (Figs. 5 and 6), raptors (*Orders Accipitriformes* and Falconiformes), game birds (*Galliformes, Gruiformes, Charadriformes, Pteroclidiformes, Columbiformes*) (Fig. 4), miscellaneous birds (*Psittaciformes, Cuculiformes, Strigiformes, Caprimulgiformes, Apodiformes, Coraciiformes, Piciformes*), and passerine birds (*Order Passeriformes*). These groups do not strictly follow any scientific or taxonomic basis. For instance, certain water birds such as *Kingfisher* may belong to an order not mentioned as water birds. BirdLife International categorized birds of Pakistan as land birds (439 species), water birds (165), sea birds (36), and migratory birds (365). The reptilian fauna (209 species) includes categories such as *testudines* (five marine turtles, eight freshwater turtles, and a single tortoise species), single species of crocodile, lizards (110 species), and snakes (83 species) (Fig. 7). The amphibian fauna (24 species) of the country is poor and is represented by a single order (*Anuran*) and two groups. Toads are represented by 11 species, while 13 frog species have been documented in the research work of Grimmett et al. (2009), GoP (2014), Khan (2014) (Fig. 8) and presented in Table 1 (Fig. 3).

Pakistan does not have high species endemism (Table 1). Reptiles dominate the list of endemic wild fauna of the country with as many as 36 known species. Only 7 anuran and 6 mammalian species are known to exist exclusively within the territorial limits of the country. The reason for this low endemism may be the connectivity of Pakistan with neighboring countries through corridors formed by the mountain ranges, deserts, oceans, and plains. So far, there is no exotic mammalian species in the wild in Pakistan (GoP 2014). The country is suffering from continuing loss, fragmentation, and degradation of natural and modified habitats. It is severely faced with biodiversity loss due to the shrinking of forests at an alarming rate, fragmentation and reduction of fertile lands, and degradation of natural resources (Baig and Aldosari 2012).

Table 1 Species richness and endemics for major plant and animal groups in Pakistan

Group	Total number reported	Endemic	Threatened
Mammals	198	6	20
Birds	690	N/A	25
Reptiles	229	36	6
Amphibians	24	7	1
Fish (freshwater)	198	29	1
Fish (marine) including 43 species of sharks	1000	–	5
Invertebrates	5000	–	2
Marine Molluscs	700	–	8
Crustaceans (Marine)	287	–	6
Annelids (Marine)	104	–	1
Land snails	100		
Nematodes	355		
Insects	> 5000	–	–
True bugs	1000		
Butterflies and moths High endemism in the *Satyrids, Lycaenids,* and *Pierids* families	400		
Flies	110		
Termites	49		
Higher plants	7000	380	N/a
Pteridophytes	200	–	N/a
Bryophytes	1126		
Ferns	133		
Algae	913	20	N/a
Fungi	> 4500	2	N/a
Crop Genetic Diversity			
Cultivated plants Major crops: wheat, rice, maize, barley, pulses, oil seeds, cotton, sugarcane, tobacco, vegetables and fruits (both tropical and temperate)	3000 taxa		
Wild relatives of cultivated crops	500		
Livestock Genetic Diversity			
Buffalo Nili-Ravi and Kundi	2		

(continued)

Table 1 (continued)

Group	Total number reported	Endemic	Threatened
Cattle Dairy breeds: Sahiwal, Red Sindhi; draught breeds: Bhagnari, Dhanni, Dajal, Lohani, Rojhan, and dual-purpose breed: Tharparkar or Thari	8		
Yak	1		
Goat	25		
Sheep 14 are thick-tailed and 14 thin-tailed	28		
Horse	1		
Camel	4		
Poultry	3		

Source GoP (2000, 2014)

Fig. 2 Female Barking Deer (*Muntiacus muntjak*). *Photo Credit* Abdul Hadi (abdulhadi@gmail.com)

2.1 Protected Areas in Pakistan

Three types of special areas were envisaged by Wildlife Enquiry Committee (WEC) after the World Wildlife Federation (WWF) expeditions in the 1960s. The committee identified the need to establish 5 national parks, 18 wildlife sanctuaries, and 52 game reserves. Consequently, these protected areas were legally established through wildlife conservation/preservation legislation by the provinces and territories, including Northern Areas (NA) and Azad Jammu and Kashmir (AJ and K) and Islamabad Capital Territory (ICT) between 1972 and 1979. New areas were

Fig. 3 Flying Fox (*Pteropus giganteus*). *Photo Credit* Mohammad Shahzaib (zs585341@gmail.com)

Fig. 4 Kalij Pheasent (*Lophura leucomelan*). *Photo Credit* Mohammad Shahzaib (zs585341@gmail.com)

Fig. 5 Little Egret (*Egretta garzetta*). *Photo Credit* Mohammad Shahzaib (zs585341@gmail.com)

Fig. 6 Common Coot (*Fulica atra*). *Photo Credit* Mohammad Shahzaib (zs585341@gmail.com)

subsequently added to the list of Protected Areas (PAs) by the provinces/territories. Community Conservation Areas have also been added to the list of PAs since the 1990s (Anwar 2007).

Fig. 7 Garden Lizard (*Calotes versicolor*). *Photo Credit* Mohammad Shahzaib (zs585341@gmail.com)

Fig. 8 Bull Frog (*Hoplobatrachus tigerinus'*). *Photo Credit* Mohammad Shahzaib (zs585341@gmail.com)

2.2 Current Situation

Initially, three categories of PAs were established in Pakistan including national park, wildlife sanctuary, and game reserve, all on public land. Recently, wildlife legislation has been revised in Khyber Pakhtunkhwa, AJ and K, and Baluchistan, in which additional PA categories have been added, including private game reserve, community conservation/managed area, biodiversity reserve, wildlife refuge, wildlife park, biosphere reserve, site of special scientific interest, national natural heritage site, sacred protected site, conservancy, and conservation area. A summary of PAs in Pakistan is provided in Table 2 (GoP 2019).

3 Climate Change and Biodiversity: Global and National Facts

IPCC (2007) predicts that an increase of 1.5–2.5 °C would threaten 20–30% of plant and animal species of the world with extinction. A 1 °C rise in temperature may shift the zone of occurrence for several specialist species by 160 m vertically and 160 km horizontally (Thuiller 2007). Two-thirds of 35 butterfly species assessed in Europe shifted their ranges northwards by 35–240 km (Parmesan et al. 1990). Climate change may alter the distribution and range of species and populations; change species composition; raise mortality due to flooding, storms, or drought; alter water chemistry affecting calcification rates of marine organisms; increase habitat loss and fragmentation affecting populations; and reduce the productivity of both pelagic and coastal ecosystems and fisheries (Parmesan 2006; Bellard et al. 2012).

A rise in the sea temperature will cause bleaching and mass die off in corals (Cinner et al. 2012; Hoegh-Guldberg and Bruno 2010). There is a positive correlation between ecosystem services and functions and marine species diversity (Worm et al. 2006). Climate change is expected to impact breeding, longevity, and development of fish, hence reducing the productivity of marine ecosystems (Brander 2007). Aquatic ecosystems are highly sensitive to variations in weather and climate, and they impact the pattern of precipitation, evaporation, flood, drought, and other factors affecting freshwater supply and quality (IPCC 2007).

Tropical forests harbor about half of the world's biodiversity. The productivity, stability, and resilience of forest ecosystem are largely determined by their biodiversity (Thompson et al. 2009). Forests provide services such as production of oxygen, regulation of climate, and carbon sequestration at regional and global scales (Malhi et al. 2008). Changing climate patterns may manifest as loss of forest biodiversity (Rull and Vegas-Vilarrúbia 2006). Mitigation of natural hazards is another significant regulating service performed by the ecosystems (Munang et al. 2013). Many species of crustaceans, fish, and reptiles use mangrove forests as breeding sites and nursing grounds. Studies have suggested an important role for these forests in reducing the impacts of tsunami by absorbing high energy waves (Danielsen et al. 2005; Kathiresan and Rajendran 2005).

About 15–37% of plant and animal species are vulnerable to climate change-induced extinction in next 50 years (Thomas et al. 2004). Ecosystems have already begun responding to the changing climate (Parmesan and Yohe 2003; Root et al. 2003) at various levels. Europe, Australasia, Antarctica, and Asia have been experiencing

Table 2 Summary of protected areas in Pakistan in 2019

Province/territory	NP	WS	GR	CCA/ CGR	PGR	MCA	WR	WP	Total	Area under Pas (ha)	% age of area
ICT	1	1	1	0	0	0	0	0	3	93,186	79.9
Azad Jammu and Kashmir	8	1	11	0	0	0	0	0	20	123,762	9.3
Balochistan	3	14	6	3	0	3	0	0	29	2,472,960	7.12
Gilgit-Baltistan	5	2	5	48					60	4,527,200	62.04
Khyber Pakhtunkhwa	6	3	38	90	16		2	8	163	1,065,453	10.47
Punjab	4	37	23	4	5			16	89	1,909,922	9.3
Sindh	1	34	13	0	0	0	0	0	48	1,855,981	13.17
Total	28	92	97	145	21	3	2	2	412	12,048,464	13.66

Source GOP (2019)

Key *NP* National Park; *CCA* Community Conservation Area; *WS* Wildlife Sanctuary; *CGR* Community Game Reserve, *GR* Game Reserve; *MCA* Marine Conservation Area, *PGR* Private Game Reserve, *WR* Wildlife Refuge, *WP* Wildlife Park changes in the climate. These effects include changes in migration of birds and mammals; breeding and hibernation in amphibians; shift in distribution of plants and invertebrates; and alteration of ecological species/communities geographical distribution (Walther et al. 2002; Root et al. 2003; Parmesan 2006). A variety of Lemur species in Madagascar are expected to be affected due to a rise of a fewer degree (2–4 °C) making them shift their distribution range (Brown and Yoder 2015). The rise in global temperature may bring about changes in the vegetation structure, especially of bamboo, as the habitat of the Giant Pandas (*Ailuropoda melanoleuca*).

The migration and breeding of marine turtles, such as the Green Sea Turtle (*Chelonia mydas*), Leather-back Turtle (*Dermochelys coriacea*), and Logger headed turtle (*Caretta caretta*) are influenced by climate change. Hence, populations of marine turtles are likely to be hit as their nesting beaches are inundated. It is predicted that a rise in sea level of 0.5 m might result in the loss of 32% of sea turtle nesting grounds (Fischlin et al. 2007).

The situation in Pakistan is similar to the global trend. Pakistan has been ranked at 13th and 16th positions among the most affected countries due to changes in climate by Maple Croft Climate Change Vulnerability Index (CCVI) and German Watch. Losses due to climate change are estimated to be about 5% of the country's GDP ($14 billion per year). The rise in temperature and CO_2 levels is expected to increase extreme conditions.

Below, we mention the status of some ecosystems in Pakistan and the impact of climate change, wherever possible:

Aquatic Ecosystem: The Indus is habitat to 147 fish species, of which 22 are found nowhere else in the world. It hosts the endangered Indus River Dolphin, one of the world's rarest mammals, with a population of no more than 1100 individuals (WWF 2005). Higher vulnerability of such an ecosystem can cause irreversible biodiversity loss. As per the IPCC (2007) report, aquatic ecosystems are highly sensitive to weather variations.

Avian biodiversity: Fluctuations in water level throughout the year in response to rainfall influence the characteristics of Uchalli Wetland complex (Uchalli, Khabbaki, and Jahlar lakes) in Pakistan. The complex was known to host a number of globally threatened bird species such as White-headed Duck. After 1997, the area of the complex declined to 27% (from 1243 to 336 ha), adversely affecting populations of migratory birds (Ali 2005). There was significant positive correlation between the amount of precipitation and bird counts in this wetlands complex. The study identified climate change as the major threat to the wetland complex and its avian biodiversity.

Marine Turtles in Pakistan: Globally, threatened species of marine turtles—such as Green Turtle (*Chelonia mydas*) and Olive Ridley Turtle (*Lepidochelys olivacea*)—migrate from deeper oceans to coastal areas to lay eggs on sandy beaches of Sindh and Baluchistan Provinces during their breeding season (Firdous 2001). A long-term study on the distribution of nesting incidences of these turtles showed a decreasing trend in the number of egg-laying females recorded at Sandspit, Karachi, for both species (Qureshi and Ali 2011). Migration and breeding in these marine turtles are influenced by climate change in two ways: Firstly, an increase in temperature results in sex biased hatchlings; secondly, climate change is expected to raise sea levels, causing higher and stronger tides, thereby destroying turtle nesting sites (Warren et al. 2018). Hence, populations of marine turtles are likely to be hit as their nesting beaches are inundated.

Amphibians: The areas of Northern Punjab, Azad Jammu and Kashmir, and Gilgit-Baltistan have relatively high degree of endemism for anurans (Khan 2006). Notable anuran fauna of these areas includes Himalayan Toad (*Duttaphrynus himalayanus*), Ladakh Toad (*Bufotes latastii*), Swat Green Toad (*Bufotes pseudoraddei*), Batura Glacier Toad (*Bufotes baturae*), Kashmir Torrent Frog (*Allopaa barmoachensis*), Hazara Torrent Frog (*Allopaa hazarensis*), and Murree Hills Frog (*Nanorana vicina*), which are adapted to climatic conditions of these areas. The data are not available in relation to climate change and amphibian populations in Pakistan. We believe that these species might face the same threats to their populations and survival as most other amphibians elsewhere in the world. Likewise, the arid terrain of the Potohar region and western parts of the country are hotspots of gecko endemism. Though these species are not as vulnerable as amphibians, their diversity and distribution may experience some change due to rising temperatures.

Agriculture: Agriculture is the mainstay of Pakistan's economy, and it accounts for 21% of the GDP. Around 67% of the population is linked directly or indirectly with agriculture. Temperature and rainfall are the main factors influencing the yield of major crops across the Pakistan; therefore, any changes in temperature or precipitation patterns will affect crop yields. Hussain and Bangah (2017) reported that wheat productivity has been impacted more in Northern Irrigated Plan zone by average temperature and in northern dry mountain region by rainfall. Rice yield has been affected by rise in average temperatures in the dry mountains and due to rainfall variability in the Indus Delta region. Sugarcane productivity has been affected due to similar reasons. In northern dry mountain zone, maize productivity has been severely impacted compared to other zones. Wheat yield decreased by 7% in Swat district and 14% in Chitral district (Hussain and Mudasser 2007), whereas it decreased by 6–9% in sub-humid, semiarid, and arid zones (Sultana and Ali 2006). A more than 3 °C rise in temperature could decrease wheat yield in arid, semiarid, and sub-humid zones, but increase the yield in humid zone (Aggarwal and Sivakumar 2010).

Livestock: Livestock is a vital component of Pakistan's economy, contributing about 11.2% to its GDP. Livestock is a source of invaluable livelihood for rural and middle grade agri-business holders. It can play a major role in poverty alleviation in rural areas of the country. The livestock sector accounted for about 60.5% of the agriculture sector in 2018–19. Sejian et al. (2015) reported that climate change affects livestock through loss of their body weight, disease occurrences, reproduction, metabolic activity, and milk production. It indirectly affects them by reducing their feed resources, pasture availability, and water. Rangeland degradation is more likely to occur during the extreme events such as droughts and floods as a result of climate change. Hence, increased climatic variability will increase the risk of rangelands degradation which affects livestock. Rangelands can sustainably produce a variety of goods and services even in the face of extreme climatic events, if managers respond quickly and appropriately to changes (Getachew 2017).

4 Pakistan's Response to Climate Change and Biodiversity Concerns

Pakistan has responded to the threat of climate change in a way that seems adequate and in line with international efforts. The country developed and launched the National Climate Change Policy (NCCP) in 2012, the Biodiversity Action Plan (BAP) in 2000, and the National Biodiversity Strategy and Action Plan (NBSAP) in 2015. Some other steps taken are summarized in this section.

4.1 Vision 2030

The main focus of this Vision 2030 document is adaptation, in view of Pakistan's high vulnerability to the impacts of climate change including inter alia, degraded ecosystems, high levels of rural poverty, illiteracy, and marginalization of women. Nonetheless, mitigation measures for the sectors of energy, transport, forestry, industry, agriculture, livestock, and town planning are also part of the policy.

4.2 National Climate Change Policy

The policy aims to incorporate climate change adaptation in vulnerable socioeconomic sectors of Pakistan and to guide the country toward climate adaptable development. The objectives of the policy are as follows:

- Addressing climate change-related issues for achieving sustainable economic growth;
- Amalgamation of the policy with several other existing related national policies;
- Adoption of pro-poor, gender-sensitive mitigation in a cost-effective manner;
- Ensuring food, water, and energy security;
- Reduction of risks posed by extreme weather events such as storms, floods, and drought;
- Reinforcing decision making and coordination mechanisms among ministries;

- Coherent use of opportunities such as financing available at the national and international level;
- Promotion of both public and private investments in climate change adaptation;
- Reinforcing capacity and skills of institutions; and
- Boosting natural resource conservation and long-term sustainability.

The NCCP prioritizes adaptation over mitigation efforts for the country with a suggested set of sector-level adaptation measures, which are further prioritized and categorized for short-, medium-, and long-term implementation through important policy guiding documents, such as the Framework for Implementation of Climate Change Policy (2013) and the Work Program on Climate Change Adaptation and Mitigation in Pakistan (2014).

4.3 National Biodiversity Strategy and Action Plan

Another important policy tool was the Biodiversity Action Plan (BAP) for Pakistan in 2000, which was revised as the National Biodiversity Strategy and Action Plan (NBSAP) in 2015. The goals of the BAP and NBSAP are as follows:

- Conserving components, species, gene, and communities/habitat of biological diversity through *in-situ* and *ex-situ* conservation and curbing illegal trade in wildlife and timber; and
- Mainstreaming biodiversity as an integral component of human development through creating awareness about biodiversity goods and services and their contribution in human well-being, sustaining development outcomes, and promoting integration with other key sectors including, but not limited to, agriculture, poverty alleviation, climate change, health, democracy and governance, economic growth, and trade.

The five strategic goals of the BAP and NBSAP are as follows:

- Tackling the main threats that underpin the survival of biodiversity through discerning connectivity across government and society;
- Lessening the direct pressures on biological diversity and promoting sustainable use;
- Improving the state of biodiversity elements;
- Augmenting gains and benefits arising from biodiversity and ecosystem services to all; and
- Strengthening implementation through participatory planning, knowledge management, and capacity building.

4.4 Green Pakistan Program/Ten Billion Trees Tsunami Program

The main objective of the program is to facilitate the transition toward an environmentally resilient Pakistan by mainstreaming notions of adaptation and mitigation through ecologically targeted initiatives such as afforestation, biodiversity conservation, and enabling policy environment. The program has been scaled up in 2018 to Ten Billion Trees Tsunami Program (TBTTP) aiming at revival of forestry and wildlife resources in light of international conventions and national and provincial legislative frameworks. The program has three components: enhancement of forest cover and management of plantations and state, guzara, and reserve forests; biodiversity conservation and establishment of 725 acres of Zoo-cum Botanical Garden, Islamabad; and institutional strengthening of Zoological Survey of Pakistan.

5 Gaps and Challenges in Conserving Biodiversity

Although Pakistan has taken various steps for the conservation of biodiversity in the context of climate change, a number of challenges/gaps still exist to be addressed for better biodiversity conservation (Anwar and Shank 2000). However, a few gaps, based on review of literature, still exist which are listed here (Fig. 9):

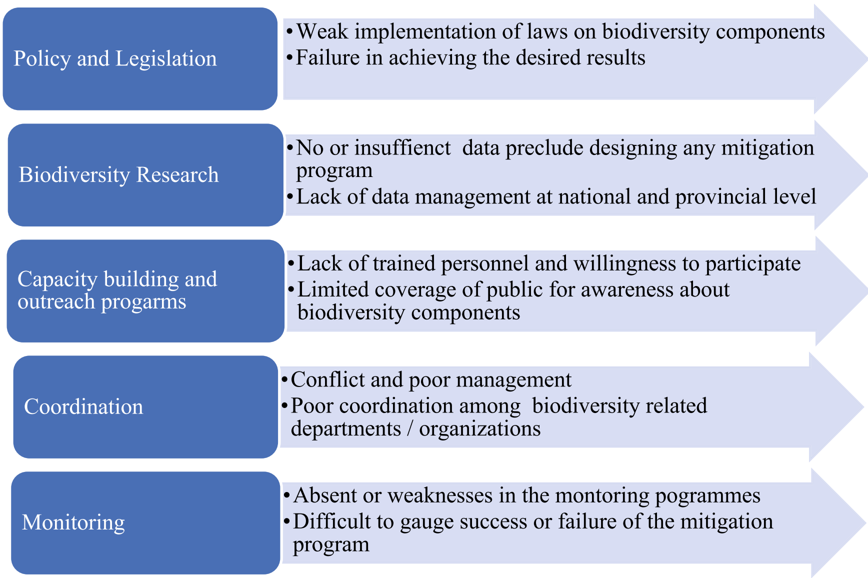


Fig. 9 Five major gaps and challenges in conserving biodiversity in Pakistan. *Source* Extracted from the review of literature in previous sections

- Weak policy and weak implementation of existing plans;
- Lack of awareness among masses and decision makers about biodiversity components;
- Lack of integration of biodiversity conservation measures into sectoral initiatives;
- Weak understanding of all aspects of biodiversity and effective means for ensuring their sustainable use;
- Absence or weak community-based biodiversity management systems;
- Lack of monitoring systems of key elements of biodiversity;
- No assessment of interaction among different socioeconomic factors pertaining to sectors like water, agriculture, and forestry sectors;
- Dearth of research on identification of the impact of climate change on local livelihood and ecosystem resilience;
- Poor climate monitoring network in Hindu Kush-Karakoram-Himalayan region; and
- Weak regional understanding and cooperation related to biodiversity by enhancing access to information.

5.1 Weak Legislation and Implementation of Policies and Laws

Policies and laws for the conservation of different components of biodiversity have been developed by the government, including forest, fisheries, and wildlife. The implementation of these policies and laws rests with provinces in their territories and the Capital Development Authority (CDA) in the federal capital territory. All the proposed developmental projects undergo an Initial Environmental Examination (IEE) and an Environmental Impact Assessment (EIA) to protect biodiversity under the Pakistan Environment Protection Act 1997. Nonetheless, most personnel in the concerned departments lack required expertise for the said tasks or are not subjected to professional development (Baig and Ahmed 2007). The implementation of laws and policies in the field is also very weak. The main reason is the lack of technically trained manpower in relevant departments. Current staff of these departments does not understand the significance of biodiversity and the importance of implementing laws for its protection and conservation. Additional implementation problems include a lack of funding and weak capacity of government departments (lack of individual capacity and incentives for performance).

Poverty among the masses is another cause of biodiversity loss. The majority of people living close to natural forests and rangelands (which are sustaining biodiversity) are dependent on these natural resources for their livelihoods, for example, free roaming livestock that grazes freely and causes overgrazing on public lands and damages the natural vegetation resulting in their loss and disturbing the habitat of wildlife species.

5.2 Lack of Awareness Among Masses and Decision Makers About Biodiversity Components

People living close to the nature reserves or biodiversity-rich areas kill animals worth millions for a small meal. Precious trees and other plants, which take many years or even decades to grow and mature, are cut in a stroke by humans to cook. These people are not aware of the ecological importance of these animals and plants and their contribution to ecosystems' balance or the free services provided by such ecosystems, which are crucial for their livelihoods. Furthermore, the role of floral biodiversity in their food security is also not realized by them.

5.3 Absence or Weak Community-Based Biodiversity Management Systems

Although reasonable progress has been made in organizing the local communities in mountainous areas for biodiversity conservation, many areas are still without community-based management programs. It is necessary to engage local communities (both urban and rural) to understand both climate change and biodiversity loss to create solutions using citizen and civic movements. Biodiversity conservation policies must prioritize increasing awareness among people because very little difference can be made by mega projects (Jaffery 2018).

6 Recommendations and Conclusion

In addition to the measures already taken by the government for the conservation of biodiversity in the context of climate change, some key steps need to be taken to reduce the climate vulnerability of biodiversity. In order to understand such climate change impacts on biodiversity and identify mitigation options, we suggest initiating education, awareness, outreach, and capacity building programs. A special attention should be given to ensure active participation and support from local communities. Currently, communities falling under project areas are being contacted for raising awareness. However, all local communities residing around protected areas or areas where biodiversity is intact and the general public should also be targeted and covered under awareness campaign about biodiversity and climate change. The associated local communities need to be involved through incentives along with the government commitment for the long run (Khan and Baig 2020).

Another important step in coping with climate change-induced dynamics is building up a strong collaboration among all stakeholders such as government, local communities, civil society, planners, policy makers, and NGOs. Extension education has proved to be a successful tool in conserving and promoting biodiversity conservation (Baig and Aldosari 2012). The measures taken for the conservation of biodiversity can be augmented through efficient extension educators, public awareness, and participation of community particularly women and youth (Baig and AL-Subaiee 2011; Greentumble 2018). Additional connectivity corridors also need to be established between protected areas and other landscapes. Various low profile animal groups such as small mammals, reptiles, amphibians, and birds should also be targeted for conservation to achieve meaningful ecological balance (Khan and Baig 2020). Some policy recommendations are as follows:

- Addressing the menace of climate change in Pakistan by adopting proactive approaches. Special consideration should be given to ensure the resilience of ecosystems and continuous supply of goods and services for local communities under a changing climate. Any climate change mitigation approach should address the dynamics of social-ecological systems, integrate indigenous knowledge, and involve local communities. Currently, the awareness program has limited coverage. There is a need to widen these efforts to general public through print, electronic, and social media.
- Assessing the vulnerability of current protected areas so that mitigation and adaptive measures can be targeted. As the temperature rises, movement of species can be facilitated by establishing corridors and maintaining connectivity with nature reserves in the mountainous areas.
- Systematic afforestation and restoration of degraded ecosystems may help improve habitat quality and connectivity to lessen the impacts of climate change. Adoption of integrated and coordinated planning at a landscape level could also lead to achieving mitigation and adaptation goals.
- Research on the response of different species of plants and animals could help understand their resilience and design mitigating measures. The requirements of different sectors—such as agriculture, biodiversity, urban and infrastructure, and resource extraction—should be taken into consideration as well.
- Finally, any land policy, which aims to develop solutions addressing climate change, should not negatively impact biodiversity and local communities.

Some other suggestions regarding the mitigation of climate change-driven impacts on ecosystems, biodiversity, and communities include implementation of existing policies and laws in their true letter and spirit; developing climate-resilient dryland crop varieties; improving irrigation systems, water conservation, ditch draining in areas suffering from drought, and adopting sustainable utilization; and investing in clean energy projects. Pakistan is vulnerable to the impacts of climate change in virtually all sectors including water, agriculture, and forestry sectors. Measures need to be taken to conserve biodiversity resources in the scenario of climate change such as more stringent legislation, designing sector-specific mitigation strategies, controlling invasive and nuisance species whose spread is linked with the climate change, restoration of habitats affected by climate change, setting research priorities, and lessening the pressure on natural resources.

Acknowledgements The authors are extremely thankful to Dr. Michael R. Reed, Emeritus Professor, and former Director—International Programs for Agriculture at the University of Kentucky, USA, for reviewing the initial drafts, making helpful comments, and offering valuable suggestions. His sincere cooperation is highly appreciated.

References

Aggarwal PK, Sivakumar MV (2010) Global climate change and food security in South Asia: an adaptation and mitigation framework. Climate change and food security in South Asia. Springer, Berlin, pp 253–275

Ali Z (2005) Ecology, distribution, and conservation of migratory birds at Uchalli Wetlands Complex, Punjab, Pakistan. Ph.D. Dissertation, University of the Punjab, Lahore, Pakistan

Anwar M (1996) State of Biodiversity in Pakistan. In: Shengji P (ed) Banking on Biodiversity: report of the regional consultation on biodiversity assessment in the Hindu Kush-Himalayas, Kathmandu, Nepal, December 19–20, 1995. Kathmandu: ICIMOD

Anwar M (2007) Review of protected areas management and performance effectiveness in Pakistan. An unpublished report submitted to Ministry of Environment/IUCN-Pakistan Islamabad, 78pp

Anwar M, Shank C (2000) Developing and implementing biodiversity strategies and action plans: lessons from Pakistan. In: Biodiversity planning in Asia. IUCN regional biodiversity program, Colombo, Sri Lanka

Baig MB, Ahmed M (2007) Biodiversity in Pakistan: status challenges and strategies for its conservation. Int J Biol Biotech 4(4):283–292

Baig MB, AL-Subaiee FSF (2011) Biodiversity in Pakistan: key issues. Biodiversity 10(4):20–29.https://doi.org/10.1080/14888386.2009.9712858

Baig MB, Aldosari F (2012) An investigation into the vanishing biodiversity: implications for rural extension. Bulg J Agric Sci 18(3):403–409

Baig MB, Burgess PJ, Fike JH (2020) Agroforestry for healthy ecosystems: constraints, improvement strategies and extension in Pakistan. Agrofor Syst 1–19. https://doi.org/10.1007/s10457-019-00467-4

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. Ecol Lett 15(4):365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

Brown JL, Yoder AD (2015) Shifting ranges and conservation challenges for lemurs in the face of climate change. Ecol Evol 5(6):1131–1142. https://doi.org/10.1002/ece3.1418

Brander KM (2007) Global fish production and climate change. In: Proceedings of the National Academy of Sciences of the United States of America, vol 104, no 50, pp 19709–19714. https://doi.org/10.1073/pnas.0702059104

Cinner JE, McClanahan TR, Graham NAJ, Daw TM, Maina J, Stead SM, Wamukota A, Brown K, Bodin Ö (2012) Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. Glob Environ Chang 22(1):12–20. https://doi.org/10.1016/j.gloenvcha.2011.09.018

Danielsen F, Sørensen MK, Olwig MF, Selvam V, Parish F, Burgess ND, Hiraishi T, Karunagaran VM, Rasmussen MS, Hansen LB, Quarto A, Suryadiputra N (2005) The Asian tsunami: a protective role for coastal vegetation. Science 310(5748):643–643. https://doi.org/10.1126/science.1118387

Fischlin A, Midgley GF, Price JT, Leemans R, Gopal B, Turley CM, Rounsevell MDA, Dube P, Tarazona J, Velichko A (2007) Ecosystems their properties goods and services. Climate change 2007: impacts adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ,

Hanson CE (eds) Contribution of working group II to the fourth assessment report of the intergovernmental Panel on Climate Change. Cambridge University Press Cambridge. Assessment Report of the Intergovernmental Panel on Climate Change*,* vol 4, pp 211–272
Firdous F (2001) Sea Turtle conservation and education in Karachi, Pakistan. ASEAN. In: Pitcher NJ, Ismail G (eds) Sea turtles of the Indo-Pacific. Rev Biod Environ Conserv (ARBEC) 1–10
Getachew BF (2017) The effect of climate change on range land and biodiversity: a review. Int J Res Granthaalayah 5(1):172–182. https://doi.org/10.29121/granthaalayah.v5.i1.2017.1732
Greentumble (2018) Ten ways to protect and conserve biodiversity. Greemtumble.com
Government of Pakistan (GoP) (1992) The Pakistan National conservation strategy. Environment and urban affairs division, Government of Pakistan and IUCN-Pakistan, 378pp
Government of Pakistan (GoP) (2000) Biodiversity action plan of Pakistan. Ministry of Environment/IUCN/WWF. Islamabad, 79pp
Government of Pakistan (GoP) (2009) Fourth National report. Convention on biological diversity. Ministry of environment, Government of Pakistan. Xii+97pp
Government of Pakistan (GoP) (2014) Fifth National report on CBD, Govt. of Pakistan, ministry of climate change, Islamabad, 86pp
Government of Pakistan (GoP) (2019) Review of protected areas system of Pakistan to include new categories as provided by IUCN. Final report. Ministry of climate change, Government of Pakistan Islamabad, 80pp
Grimmett R, Roberts T, Inskipp T. (2009) Birds of Pakistan (Helm Field Guides). Yale University Press, 288pp
Hoegh-Guldberg O, Bruno JF (2010) The impact of climate change on the world's marine ecosystems. Science 328(5985):1523–1528. https://doi.org/10.1126/science.1189930
Hussain A, Bangah R (2017) Impact of climate change on crop productivity across selected agro-climatic zones in Pakistan. Pak Dev Rev 56(2):163–167
Hussain SS, Mudasser M (2007) Prospects for wheat production under changing climate in mountain areas of Pakistan—an econometric analysis. Agric Syst 94:494–501
IPCC (2007) An assessment of intergovernmental panel on climate change. Climate change synthesis report, Cam-bridge University Press, Cambridge, UK, p73
Jaffery R (2018) Pakistan's biodiversity is disappearing, but no one seems to notice. The Pulse
Kathiresan K, Rajendran N (2005) Coastal mangrove forests mitigated tsunami. estuarine coastal and shelf. Science 65(3):601606. https://doi.org/10.1016/j.ecss.2005.06.022
Khan H, Baig SU (2020) Biodiversity conservation in the Hindu Kush-Karakoram-Himalayan mountain region of northern Pakistan: overview of big mammal protection. J Mt Sci. 17(6):1360–1373. https://doi.org/10.1007/s11629-018-5113-0
Khan MS (2006) Amphibians and reptiles of Pakistan: Krieger Publishing Company Malabar. Florida 32950:311
Khan MS (2014). Amphibians of Pakistan and their conservation status. Chapter 7 In: Heatwole H, Das I (eds) Conservation biology of Amphibians of Asia. Published by Natural History Publications (Borneo), Kota Kinabalu. Sabah, Malayasia, 382pp
Malhi Y, Roberts JT, Betts RA, Killeen TJ, Li W, Nobre CA (2008) Climate change, deforestation, and the fate of the Amazon. Science 319(5860):169–172. https://doi.org/10.1126/science.1146961
Mirza ZB (1998) Illustrated handbook of animal biodiversity of Pakistan: centre for environmental research and conservation Islamabad. 99pp
Munang R, Thiaw I, Alverson K, Mumba M, Liu J, Rivington M (2013) Climate change and ecosystem-based adaptation: a new pragmatic approach to buffering climate change impacts. Curr Opin Environ Sustain 5(1):67–71. https://doi.org/10.1016/j.cosust.2012.12.001
PARC (2019) Agro-ecological zones of Pakistan. Agricultural maps of Pakistan. Available at: http://www.parc.gov.pk/index.php/en/component/content/article/43-maps/19-agrimaps. Accessed on June 06 2020

Parmesan C, Ryrholm N, Stefanescu C, Hillk JK, Thomas CD, Descimon H, Huntley B, Warren M (1990) Poleward shifts in geographical ranges of butterfly species associated with regional warming. Nature 399(6736):579–583.https://doi.org/10.1038/21181

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421(6918):37–42. https://doi.org/10.1038/nature01286

Parmesan C (2006) Ecological and evolutionary responses to recent climate change. Annu Rev Ecol Evol Syst 37:637–669. https://doi.org/10.1146/annurev.ecolsys.37.091305.110100

Qureshi N, Ali Z (2011) Climate change, biodiversity Pakistan's scenario. J Anim Plant Sci 21(2):358–363

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421(6918):57–60. https://doi.org/10.1038/nature01333

Rull V, Vegas-Vilarrubia T (2006) Unexpected biodiversity loss under global warming in the neotropical Guayana highlands: a preliminary appraisal. Glob Change Biol 12(1):1–9.https://doi.org/10.1111/j.1365-2486.2005.001080.x

Sejian V, Bhatta R, Soren NM, Malik PK, Ravindra JP, Prasad CS, Lal R (2015). Introduction to concepts of climate change impact on livestock and its adaptation and mitigation. In: Climate change impact on livestock: adaptation and mitigation. Springer, New Delhi, pp 1–23

Sultana H, Ali N (2006) Vulnerability of wheat production in different climatic zones of Pakistan under climate change scenarios using CSM-CERES-Wheat Model. In: 2nd International young scientists' global change conference. Beijing, pp 7–9

Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, BF N, Erasmus M, Ferreira de Siqueira, Grainger A, Hannah L, Hughes L, Huntley B, van Jaarsveld AS, Midgley GF, Miles L, Ortega-Huerta MA, Peterson AT, Phillips OL, Williams SE (2004) Extinction risk from climate change. Nature 427:145–148. https://doi.org/10.1038/nature02121

Thompson I, Mackey B, McNulty S, Mosseler A (2009) Forest resilience, biodiversity, and climate change. Paper presented at the secretariat of the convention on biological diversity, Montreal. CBD Technical Series, no. 43. 67pp

Thuiller W (2007) Climate change and the ecologist. Nature 448(7153):550–552. https://doi.org/10.1038/448550a

Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJ, Fromentin JM, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416(6879):389–395

Warren R, Price J, Van Der Wal J, Cornelius S, Sohl H (2018) The implications of the United Nations Paris agreement on climate change for globally significant biodiversity areas. Clim Change 147(3–4):395–409. https://doi.org/10.1007/s10584-018-2158-6

Worm B, Barbier EB, Beaumont N, Duffy JE, Folke C, Halpern BS, Jackson JBC, Lotze HK, Micheli F, Palumbi SR, Watson R (2006) Impacts of biodiversity loss on ocean ecosystem services. Science 314(5800):787–790. https://doi.org/10.1126/science.1132294

WWF (2005) WWF's Global River Dolphin initiative. WWF International: Gland, Switzerland

Maqsood Anwar Dr. Anwar is currently working as Professor and In Charge Faculty of Forestry, Range Management and Wildlife at Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Pakistan. He completed his Ph.D. in Wildlife from Utah State University, USA in 1989. He earned an M.Sc. degree in Zoology from University of Agriculture, Faisalabad. Dr. Anwar started his career as researcher in Pakistan Agricultural Research Council in 1982. He was a Ph.D. Fellow at Utah State University from 1985 to 1989 and he served in IUCN- Pakistan and Ministry of Environment, Government of Pakistan as a Biodiversity Specialist from 1997 to 2002 in a GEF-funded project: "Mountain Areas Conservancy Project". He is a member of IUCN World Commission on Protected Areas. He is a life member of Zoological Society of Pakistan. Dr Anwar has published extensively in national and international journals. His scientific interests cover wildlife ecology and conservation, biodiversity conservation, and protected areas management. He has represented

Pakistan at various international conferences. After joining the Department of Wildlife Management at PMAS- Arid Agriculture University Rawlpindi, he played a pivotal role in initiating a postgraduate degree in wildlife management for the first time in Pakistan from this university in 2007.

Muhammad Rais Dr. Muhammad is serving as an Assistant Professor of Wildlife Management at Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Pakistan. He has been working on various aspects of Herpetology in the Potohar Area, Punjab, Pakistan. He has completed three foreign training schools (USA, Australia, and India) in Herpetology. He is a member of the Conservation Planning Specialist Group, the Species Survival Commission, the Commission on Ecosystem Management, and the International Union for Conservation of Nature. His lab is currently working on diversity, abundance estimation, morphometry, population monitoring, species distribution, and space use of anurans.

Some Physiological Plant Characteristics to Adapt to the Changing Climate in Indonesia

Sandra Arifin Aziz

Abstract Indonesia is a tropical country with rainy and drought seasons. Due to climate change, the country has experienced, in the last 30 years, increasing temperatures, a significant warming trend, changing rainfall patterns, and a reduced seasonality. The country has also experienced recurrent natural disasters such as drought and flood, high humidity, soil degradation, low pH, and decreasing soil organic matters. Climate change influences plants and adaptations due to the changes affecting the biophysical environment for species survival. Extreme weather like high rainfall and strong winds will be advantageous to some perennials but may be disastrous to most annual plants, such as the essential paddy rice agriculture. This chapter provides background information on these dynamics and suggests some physiological plant characteristics to adapt to climate change in Indonesian tropical agro-systems.

Keywords Adaptation · Bioactive compound · Plant growth · Polyculture · Stresses

1 Introduction

In this chapter, some physiological plant characteristics adaptation to climate change in Indonesian tropical agro-systems are observed. In the shift in plant growth and development and how plants adjust from higher to lower altitudes, such an adaptation represents how the plant adjusts to rising temperatures.

2 Indonesia Geographic Condition and its Flora and Fauna

Indonesia is an archipelagic country with 17,508 islands (Case et al. 2007; Rintelen et al. 2017), 80,000 km of coastline, and the fourth important population in the

S. A. Aziz (✉)
IPB University, Bogor, Indonesia
e-mail: sandraaziz@apps.ipb.ac.id

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_7

world. The forest covers most of Indonesia's Island. Deforestation and land-use changes are, respectively, producing the highest percentage of the country's annual greenhouse gas emissions. These conditions make Indonesia most vulnerable to climate change. The forest itself showed a high level of biodiversity that hosts a wide array of diverse ecosystems, which consisted of abundant species because of the Indonesian geography, topography, and climate (Case et al. 2007). The Wallace Line in the middle is a line that separates edaphic differences, flora, and fauna in the western and eastern parts of Indonesia. The line covered from north to south between Borneo and Celebes and between Bali and Lombok (van Oosterzee 1997; Gallery 2016; Rintelen 2017).

The Indonesia Maritime Continent (IMC) is a distinct physical climatology of the country. As an archipelagic country, Indonesia has the world's most significant rainfall with diurnal cycles (Yamanaka 2016) and the wettest and rainfall totals spatial heterogeneity regions of the world (Lestari et al. 2019). Sumatera, Java, and Kalimantan are the main islands with these characteristics (Mori et al. 2004). The monsoons will bring extreme rainfall variation (Siswanto et al. 2015).

The daily average temperature of Jakarta, the capital of Indonesia, varies from 23 to 32 °C. The wetter season is from October to May. May to October is the dry season.[1] The minimum and maximum rainfall in rainy and dry seasons is < 200 to > 250 mm/month and < 50 to < 200 mm/month, respectively (Mulyana 1997). The relative humidity is relatively high and ranges between 60 and 90%, with rainfall measuring more than 2000 mm per year in 2015–2020 (Indonesia Statistical Center Bureau 2021).

The heavy rainfall has caused soil degradation. The average annual precipitation (AAP) has affected the availability of edaphic nutrients, soil types with low pH and organic matter, and high contents of aluminum (Rachman et al. 2021). It reduced cation exchange capacity (CEC) with low total N, P, Mg, and Ca. The K concentrations were intermediate, and the adequate cation exchange capacity (ECEC) was low (Payne and Edis 2012; Quinto-mosquera and Moreno-hurtado 2016). This diverse edaphic condition made Indonesia one of the world's centers of origin and biodiversity in the world, as stated by Nikolai Ivanovic Vavilov (1887–1943) (Gallery 2016).

Due to climate change, the country has witnessed rainfall patterns and intensity changes or reduced seasonality, rising temperature, and natural disasters such as drought and flood.

3 Climate Change Intensity and Impact in Indonesia

Climate change will affect Indonesia's ecosystems. In this perspective, the size of 100 million hectares of the tropical forest, which comprises a unique biological richness, is expected to disappear (Forest Watch Indonesia 2002). However, Indonesian people

[1] weatherspark.com, 2021.

highly depend for their food and health on plant resources and a better environmental quality (Sukara 2014).

Due to increased CO_2 concentration in the atmosphere, climate change contributes to rising temperatures and alters rainfall patterns and seasonality. The wetter drought season is promoted by reduced seasonality because of the steady precipitation increase, but the wet-season precipitation and length remained constant (Naylor et al. 2007; Murray-Tortarolo et al. 2017). Climate change made a decreasing pattern in Java, the Indonesia's southern region, but an increase mainly in the northern areas of the country, such as Kalimantan in 1931–1990 (NIC 2009).

The annual and inter-annual variations of precipitations strongly influence agricultural production in Indonesia. Predictions of the yearly cycle of precipitation suggest an increase in rainfall later in the crop year (April–June) of $\approx$ 10% but a substantial decrease (up to 75% at the tail) in precipitation later in the drought season (July–September) (Naylor et al. 2007).

3.1 Rainfall Pattern and Intensity

Rainfall is the primary variable of the Indonesia's climate[2] from the wet season (December–May) and the dry season (June–November) (Lestari et al. 2019). There were three rainfall patterns in the country: i.e., monsoonal, equatorial, and local type. The dominated uni-modal monsoon rainfall type with one peak of the rainy season for six months and the other six months is the drought season. The bimodal rainfall or equatorial type has two peaks of the rainy season. The local type is with uni-modal rainfall, but the pattern is the opposite of the monsoonal type (Lasco and Boer 2006).

Indonesia grouped rainy days as rain intensity above 1, 20, 50, and 100 mm/day in a year, mainly as a positive trend. However, sometimes it is negative with varying magnitudes (Meteorology, Climatology, and Geophysics Council of Indonesia, 2021).

Seasonality precipitation and a 30-day delay in the annual monsoon occurred with a 10% increase in rainfall later in the crop year (April–June), such as in parts of Sumatra and Kalimantan in 2080, and up to a 75% decrease in rainfall later in the drought season (July–September) (Mori et al. 2004). Climate change made Jakarta 5–15% drier during June–August in thirty years (Case et al. 2007). It suffered rainfall extremes of more than 100 mm in two days with increasing trends in rainfall more than 50 and 100 mm and the highest one percent of total rainfall events in a year between 1960 and 2010 (Lestari et al. 2019). The wettest areas include coastal regions such as Sumatra, Java, and northwest of Kalimantan (Mori et al. 2004).

---

[2] Ibid.

3.2 Temperature

The Meteorology, Climatology, and Geophysics Council of Indonesia (2021) stated that the temperature in Indonesia (data from 1981–2018) has a positive tendency with a varying magnitude of around 0.03 °C per year. It will likely increase by approximately 1 °C through 2030 and keep rising through the remainder of the twenty-first century (NIC 2009). In the last 30 years, Indonesia experienced increasing high temperatures, a significant warming trend for a growing trend of the annual mean of daily maximum and daily minimum temperatures of 0.18 and 0.30 °C decade^{-1} (Supari et al. 2017).

Crop yield has declined, partly due to rising temperatures and extreme weather events. This situation brought a problem to the biodiversity and ecosystem services changes in species distribution, reproduction timings, and phenology of plants (Cruz et al. 2007). The changes in temperature and precipitation affect water availability and food production and cause prolonged droughts and increased flooding. More frequent and severe storms increased the frequency and severity of El Niño events and fires, leading to significant agricultural losses and a substantial drop in food productivity (Case et al. 2007).

4 How Plants Respond to Climate Change in the Tropics?

Each species has a specific niche in the ecosystem (Odum and Barrett 1971). Plant responses to climate change occurred, and such responses cover organisms from genes to cells, tissues, individuals, populations, and communities (Ruthenberg 1971; Nievola et al. 2017). Organisms are linked to the conditions or factors of their physical environment, i.e., air temperature, humidity, radiation/light, and wind. Such conditions affect the immediate response in plant's temperature, water losses, respiration, and photosynthesis. Prolonged physical changes often produce an intermediate physiological response—such as temperature regulation or temporary wilting—followed by an acclimatization process. In the long run, such conditions will create an evolutionary response in genetic change or tolerances because of coupling factors, resulting in extinction. The last outcome may trigger species change in the communities (Cox and Atkins 1979; Smith and Dukes 2012; Nievola et al. 2017).

4.1 CO_2

Increasing CO_2 because of global warming has a positive effect on plant growth (Reddy et al. 2010). In *Salix* spp., higher atmospheric CO_2 and temperature both or independently regulate primary and secondary metabolism (Gallery 2016) through the resource allocation, with a resulting 'trade-off' between secondary metabolic processes, such as in isoprene biosynthesis (Austen et al. 2019). In soybean, this may increase leaf size, leaf node number, seed yield, root length, root nodules, and delayed reproductive development (Gray and Brady 2016). The increased CO_2 has targeted effects on specific cell types or cell-type specifications within the individual leaf. It alters shoot architecture and carbon metabolism by increasing the flux of carbohydrates and related metabolites needed for growth and development (Gallery 2016).

4.2 Temperature

Tropical species with limited geographic and seasonal variations in temperature are likely to be particularly sensitive to global warming. These tropical species already lived at or near the highest temperatures before global warming began and are often isolated from cool refuges (Wright et al. 2009). Temperature is a primary factor affecting the rate of plant development and changing plant metabolism (Roux et al. 2001). Warmer temperatures and more extreme temperature events will impact plant productivity. Species-specific factors relating to plant development and physiological changes will also influence yield in response to temperature (Miller and Stillman 2012; Hatfield and Prueger 2015; Gallery 2016).

Photosynthesis with more variables (Rasmusson et al. 2019) and respiration is photo-thermic dependent, while growth efficiency is temperature independent (Roux et al. 2001). The Q10 value is used as a constant value of 2.0, doubling the rate with a temperature increase of 10 °C used to predict rate changes that depend on biophysical factors. Elevated temperatures caused higher photosynthetic Q10. With increasing temperature, significant differences in both photosynthetic and respiratory rates were observed among shoots of different ages, plant tissue, and shoot age, among other parts of leaves. At the same time, there were no differences found among different leaf ranks (Rasmusson et al. 2019).

Topt is the optimum temperature for photosynthesis. That shifting Topt achieves greater photosynthesis at the growth temperature which will produce greater photosynthesis. Another mechanism is by changing the shape of the photosynthesis–temperature curve without moving Topt (Yamori et al. 2014). The temperature regulates the leaf morphology and development, the new leaf growth rate, and the morphological responses throughout a crop plant's vegetative development (Gallery 2016; Hatfield and Prueger 2015).

In the tropics, higher temperatures mostly coincided with drought or low water availability. The root and reproductive development may be affected directly by rising soil temperatures (Gallery 2016) and indirectly by changes in the shoot's physiology, development, and resource acquisition in response to warmer air temperatures or by combining both factors. In a broad sense, the rising temperature increased allocation to roots. The increasing temperatures significantly impact critical root functions,

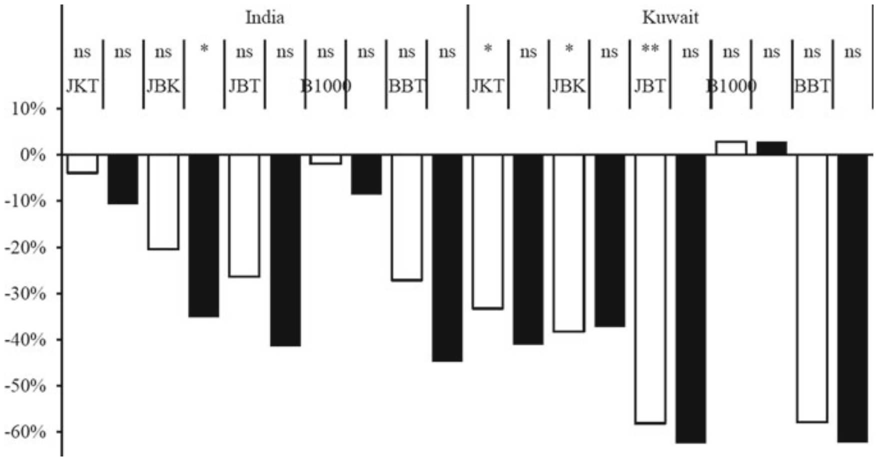


Fig. 1 Lower yield components of black cumin compared to high altitude. Filled square—low altitude; open square—middle altitude. JKT—capsule number/plant; JKB—seed number/capsule; JBT—seed number/plant; B 1000—1000 seed weight; BBT—seed weight/plant; ns—non-significant. *Source* Herlina et al. (2017)

respiration (Atkin et al. 2000), and nutrient uptake (Awal et al. 2003). Reducing flower number, increasing expression of abscisic acid/ABA response, dehydration response genes are plant's developmental and morphological responses to a higher temperature or drought escape via early flowering (Gallery 2016).

Tropical areas of low altitude have a relatively higher temperature than high altitudes. A temperature increase of 6.5 °C occurs for every 1000 m increase in the altitude (Montgomery 2006) or higher temperature in the drought season than in the wet season (Peng et al. 2004). Planting in different altitudes and comparing drought and rainy seasons showed how plants adjust to heat stress. Also, the plant morphology changes, i.e., lower LAI, lower leaf number, and smaller leaves suppressed shoot growth. The Asiatic pennywort has a higher photosynthetic rate if water availability is high (Martono 2011); this is also found in black cumin (Fig. 1) (Herlina et al. 2017) and buckwheat (Fig. 2) (Lumingkewas et al. 2015a).

4.3 Rainfall Intensity

Trees in the tropics did not grow, flower, or produce fruit year-round. Peaks in leaf flushing, flowering, and fruiting coincided with the high irradiance and low water stress associated with the onset of the wet season (Rao and Sthapit 2012; Ramadhan et al. 2015; Gallery 2016; Aziz 2017). Table 1 shows the phenology of *Stelechocarpus burahol*.

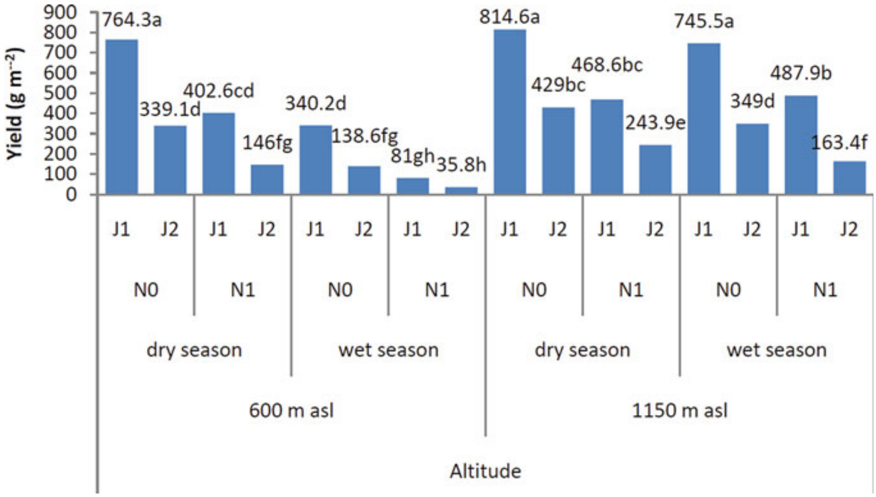


Fig. 2 Lower yield on buckwheat in low altitude. 200 plant m-2 (2.5 cm × 20 cm) (J1); 50 plant m-2(10 cm × 20 cm) (J2); without shading (N0); and shading using 55% paranet (N1); drought season (M1); wet season (M2); low altitude (600 m asl) (T1), and high altitude (1150 m asl). *Source:* Lumingkewas et al. (2015b)

Physicochemical edaphic factors strongly defined the vegetation structure and physiognomic properties in the tropics. Climatic gradient, parent material and soil age, topography and landscape stability, and atmospheric deposition result in substantial heterogeneity in soil nutrient availability from local to regional scales (Ruthenberg 1971; Gallery 2016).

Less rainfall in the drought season caused stress and significant losses in plant production and agricultural yield. The magnitude of the effects depends upon the developmental stage at which plants experience drought stress (Gallery 2016), soil-related parameters such as soil texture (Bodner et al. 2015), and soil organic matter (Mualim 2012; Rachman et al. 2021).

4.4 *Reduced Seasonality*

The dry-season precipitation increased steadily, while wet-season precipitation remained constant, reducing seasonality at a global scale. The decrease in seasonality was not due to a change in dry-season length but in precipitation rate; thus, the dry season is, on average, becoming wetter without changes. These changes in precipitation led to changes in evapotranspiration, thus affecting vegetation productivity or generating an increase in the wet-season rainfall that changes into runoff (Murray-Tortarolo et al. 2017). Three decades of observations in vegetation seasonality marked seasonality trends for the period 1982–2013. More than one-third of

Table 1 Leaf emergence, flowering, and fruiting time with the rainfall intensity in *Stelechocarpus burahol*

Plant phase	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Leaf emergence												
Flowering time												
Fruiting time												
Rainfall intensity (mm/month)	509.8	406.0	289.8	216.0	399.3	62.4	361.0	280.1	503.2	336.7	246.1	246.1

 = young, medium, and mature leaf (left–tight);  = fruit;  = flower. Source: Ramadhan et al. (2015)

the global vegetated area experienced this (Ye et al. 2021). Extreme weathers like high rainfall and strong winds will be advantageous to some perennials but may be disastrous to most annual plants (Dulbari et al. 2021).

Budburst, growing season, flowering time, and flowering duration adapted to the seasons (Zhao et al. 2013; Ramadhan et al. 2015). Flushing occurred in the wet season, whereas fruiting happened in the drought season, such as in *Zingiberaceae* (Souvannakhoummane 2014). Budburst or extension in the growing season appeared to be mainly influenced by increasing temperature than the rainfall. The flowering duration was shortened by average, most likely to result from the decline in sunshine duration during the rainy season (Zhao et al. 2013). The reduced seasonality will shift the plant phenological events. Advanced, delayed, or no change in emergence makes the plant always vegetative (Scranton and Amarasekare 2017). The long-term reduced seasonality in the end probably drove the species into extinction if the species could not adapt to these changes (Román-Palacios and Wiens 2020).

The ways to solve vulnerability to climate change are using, i.e., integrated agro-ecosystems, polyculture, or crop diversification (Cox and Atkins 1979). Other measures include increased water storage, water efficiency, re-prioritizing current water use, investment in drought-tolerant and salt-tolerant crops, better early El Niño warning systems, and reduced deforestation and forest protection (Forest Watch Indonesia 2002).

Environmental stresses will produce reactive oxygen species (ROS) that will promote the amount, types of metabolites (Lin et al. 2016; Sharma et al. 2019), and the changes of the secondary metabolite pathway (Austen et al. 2019). Waterleaf (*Talinum triangulare*) experienced this phenomenon (Mualim 2012).

4.5 Plant Phenotypes and Physiological Characteristics to Adapt to Climate Change

Specific developmental responses to drought vary among plant organs and tissues. Drought tolerance is a critical factor for agriculture in the twenty-first century as it is a significant determinant of plant survival in natural ecosystems and crop productivity (Brilhaus et al. 2016). In a broad sense, drought stress causes plants to invest resources in root tissue at the expense of shoot tissue. At the molecular level, the metabolite profiles of each tissue shift the allocation of resources from shoots to roots in response to drought stress (Gallery 2016). Changes in plant metabolism (Mualim et al. 2012; Winter and Holtum 2014; Brilhaus et al. 2016; Zhang et al. 2019), species, genotype, physiology, developmental stage, and environmental factors during growth determined the type and concentration(s) of a second molecule(s) produced by a plant (Isah 2019). Root elongation is often maintained in drought while shoot growth ceases. In times of water deficit, plant's investment in root tissue is more profitable than in leaf tissue, reducing the area for water loss via transpiration (Gallery 2016).

Tropical environment conditions made a multi-story physiognomy of the tropical rainforests (Baur and Fellow 1961). The type of agriculture required is a polyculture system that consists of various plants—starting from the bottom to the highest part, namely from the kinds of tubers or rhizomes, annual plants, shrubs, and trees of different heights. The diversity of existing plant species will take advantage of the resources above and in the soil (Fujii et al. 2018).

Changes in Plant Phenotype: A Fast-Growing Plant with Less Shoot and More Roots

The tropical organisms proliferate under increased temperatures and rainfall regimes to better compete for limited resources, leading to faster metabolisms and uptake rates. Either process can push bioaccumulation toward extreme values. For plants, at least warm, moist conditions can give rise to physiognomic features, such as deep or widely spread roots or large leaves, which increase bioaccumulation (Payne and Edis 2012; Gallery 2016). Plant with high photosynthesis and low respiration could meet the fast-growing need (Smith and Dukes 2012).

There will be changes in species types and species composition due to climate change. Choosing a different kind of plant is a must to survive climate change. One of them is using fewer shoot plants that are deeply rooted—such as tuber plants, bulbs, rhizome, shrub, and trees—or early plant harvesting in the vegetative phase.

Improving the plant water-use efficiency (WUE) with no impairment in carbon assimilation and a plant's ability could be the way to cope with reduced water availability. Stomata generally open in response to light (except Crassulacean Acid Metabolism stomata), low CO_2 concentration, high temperatures, and low vapor pressure difference (VPD). At the same time, low light intensity or darkness, elevated CO_2, and high VPD made stomata closure (Lawson and Blatt 2014).

Flowering All Year Round

Reduced seasonality made the plant life cycle shortened or continued in the vegetative phase (Scranton and Amarasekare 2017). The plant that flowers all year-round has a better chance to survive than the tropical prototype type, with the flushing in the wet season and flowering when the C/N ratio pushes the plant to the generative phase (Davenport 2003). Murray-Tortarolo et al. (2017) stated that a shorter dry season means more extended foliated periods, and rainfall during the dry season can cause re-foliation of many tree species. This condition prolonged the plant's vegetative phase.

Pollination and its developmental stages are the most sensitive phenological stages to temperature extremes across all species that significantly affect production. Few adaptation strategies are available to cope with temperature extremes at this developmental stage other than to select for plants that shed pollen during the cooler periods of the day or are indeterminate, so flowering occurs over a more extended period of the growing season (Hatfield and Prueger 2015).

C4/CAM Metabolism Plant or Shift from C3 to C4/CAM Metabolisms or Developing Heat and Drought-Tolerant Crop

Reversible photosynthesis from C3 to weakly expressed crassulacean acid metabolism (CAM) is the way to respond to drought stress (Zhao et al. 2013; Winter and Holtum 2014; Brilhaus et al. 2016). Facultative CAM describes the optional use of CAM photosynthesis; under drought stress conditions, plants that otherwise employ C3 or C4 photosynthesis, such as *Portulaca oleracea* and *Talinum triangulare* would use the CAM photosynthesis (Winter and Holtum 2014).

Most indigenous species from tropical lowlands are heat and drought-tolerant species/crop/varieties. These species' metabolism should change to facultative C4/CAM photosynthesis to solve climate change issues. On producing green shallot, Putri (2021) demonstrated that planting green shallot in the highlands showed that plant and fresh leaf weight was higher in the rainy season than in the drought season. The production of green shallot in the highlands both in the rainy and drought seasons was higher than in the lowlands in the rainy season, whereas planting in the drought season is not recommended (Table 2).

One of the unique tropical areas is the paddy conditions (Payne and Edis 2012). There is a need for adaptation strategies in Indonesian rice agriculture, including increased investments in water storage, drought-tolerant crops, crop diversification, and early warning systems because of climate change (Naylor et al. 2007). Wide temperature-tolerant varieties grew for high-temperature stress on rice growth and productivity. The additive gene action controlled the filled grain number per panicle which is suggested as a selection character (Wirnas et al. 2020). Rice varieties that can rapidly germinate and produce robust seedlings are suitable for the direct-seeded (DSR) system. Rapid growing and vigorous seedlings could support healthy plant growth and adapt to environmental changes. Accumulation of biomass at the germination stage can support the seedling to grow photosynthetic organs, and it will help suppress competition with weeds in the direct-seeded system. These results reinforce the information that the size and shape of seeds are closely related to the early seedling vigor traits of rice plants (Fauzi et al. 2021).

Table 2 T-test for growth variables and yields of shallots on the highlands in the rainy and drought seasons

No.	Variables	Average in the wet season	Average in the drought season	*P*-value
1	Anthocyanins (mg g^{-1})	0.37	0.63	0.012*
2	Carotenoids (mg g^{-1})	2.30	2.69	0.001*
3	Total N leaf (%)	3.61	2.25	0.003*
4	Total P leaf (%)	0.37	0.23	0.004*
5	Total K leaf (%)	2.17	4.40	0.002*
6	Total S leaf (%)	0.52	0.50	0.472
7	Plant height (cm)	49.07	46.09	< 0.001*
8	Leaf number	48.5	38.8	< 0.001*
9	Tillers number	3.6	3.7	ns
10	Leaf area (cm^2)	1506.64	1278.18	< 0.001*
11	Leaf wet weight (g)	104.61	95.35	< 0.001*
12	Leaf dry weight (g)	9.66	7.73	< 0.001*
13	Root wet weight (g)	4.34	4.68	< 0.001*
14	Root dry weight (g)	0.40	0.41	0.041*
15	Total wet weight (g)	142.32	140.48	ns
16	Total dry weight (g)	13.20	12.74	0.015*
17	Yield (t ha^{-1})	15.90	15.69	ns
18	Total phenol (mg g^{-1})	8.69	9.78	0.015*
19	Total flavonoids (mg g^{-1})	6.02	8.44	< 0.001*

Source Putri (2021)

Shift to Different Secondary Metabolite Biosynthesis Pathway

The change in the existing ecosystems due to predicted future global climatic changes can cause survival of only certain types of plants, possibly due to their high antioxidant capacity (Réblová 2012). Environmental stress can alter secondary metabolite biosynthetic pathways (Verma and Shukla 2015). The primary path is the shikimic (Hassanpour et al. 2011), then phenylpropanoid, and/or malonic acid (phenolic groups), and the mevalonic acid (Pagare et al. 2015).

The total phenol contents are produced through the shikimic acid pathway to phenylpropanoid pathway (Lin et al. 2016; Wang et al. 2019) and/or malonic acid pathway (Shannon et al. 1963; Spangenberg 2014). A study in *Talinum triangulare* showed that total phenolics (Mualim 2012), the most widely distributed secondary metabolites, synthesized in higher quantity in response to stress (Lin et al. 2016), like in drought season compared to the wet season. In contrast, the total flavonoids decrease (Fig. 1). In the rainy season, *Talinum triangulare* generated phenolics and

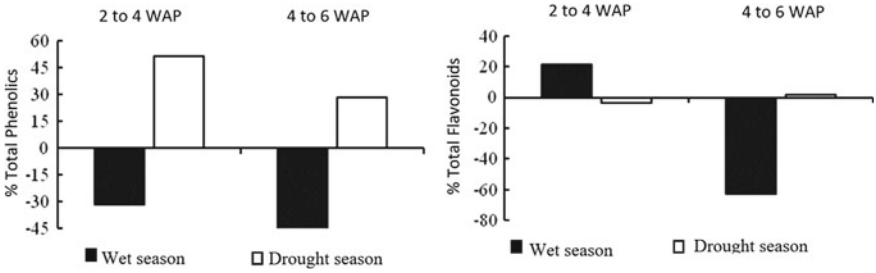


Fig. 3 Phenolic and flavonoid compound content dynamics related to the antioxidant capacity waterleaf with organic and inorganic fertilization. **a** Total phenolics content, **b** the total flavonoid content. A positive value indicates an increase, and a negative value shows decline. WAP—weeks after planting. *Source* Mualim (2012)

flavonoids mostly in the shikimate pathway. It occurred through the phenylpropanoid pathway and only a little from the malonic acid pathway. Still, in the drought season, an increase in the malonic acid pathway was observed to produce the total phenolics. In the primary metabolic pathway, acetyl Co-A, aliphatic amino acids, protein, and chlorophylls were increased. A decrease in the secondary metabolic pathway in aromatic amino acids, phenylalanine ammonia-lyase activity, phenylpropanoid pathway, and total phenolics were observed (Fig. 3) (Mualim 2012).

5 Conclusion

There will be changes in species types and composition due to climate change impacts which affect plant species in their morphology, phenology, primary, and secondary metabolisms. Therefore, the plants that can adapt to climate change would survive, but those will not go extinct.

References

Plant Resources of South-East Asia [PROSEA] (1991) No. 2: Edible fruits and nuts. In: Verheij EWM (ed) Prosea Foundation, Bogor (Indonesia) eng; Coronel RE (ed). https://agris.fao.org/agris-search/search.do?recordID=XF2016030905

Atkin OK, Edwards EJ, Loveys BR (2000) Response of root respiration to changes in temperature and its relevance to global. New Phytol 147(1):141–154. https://doi.org/10.1046/j.1469-8137.2000.00683.x

Austen N, Walker HJ, Lake JA, Phoenix GK, Cameron DD (2019) The regulation of plant secondary metabolism in response to abiotic stress: interactions between heat shock and elevated CO_2. Front Plant Sci 10:1–12. https://doi.org/10.3389/fpls.2019.01463

Awal MA, Ikeda T, Itoh R (2003) The effect of soil temperature on the source-sink economy in peanut (*Arachis hypogea*). Environ Exp Bot 50(1):41–50. https://doi.org/10.1016/S0098-8472(02)00111-9

Aziz SA, Ghulamahdi M (2011) Red guava leaf harvesting impacts flavonoid optimization in different growth phases. Hayati J Biosci 18(2):97–102

Aziz SA (2017) Guava leaf phenolics and flavonoids production. Lambert Academic Publications, p 135

Baur GN, Fellow AM (1961) *The ecological basis of rainforest management* (Issue 1960). http://www.fao.org/3/ax363e/ax363e.pdf

Bodner G, Nakhoforoosh A, Kaul HP (2015) Management of crop water under drought: a review. Agron Sustain Dev 35(2):401–442. https://doi.org/10.1007/s13593-015-0283-4

Brilhaus D, Bräutigam A, Mettler-Altman T, Winter K, Weber APM (2016) Reversible burst of transcriptional changes during induction of crassulacean acid metabolism in *Talinum triangulare*. Plant Physiol 170(1):102–122. https://doi.org/10.1104/pp.15.01076

Britannica (2021) The Editors of Encyclopedia. "Nikolai Vavilov" Encyclopedia Britannica, 22. https://www.britannica.com/biography/Nikolai-Vavilov. Accessed on 16 Apr 2021

Indonesia Statistical Center Bureau (2021) Rainfall 2015–2020. https://www.bps.go.id/searchengine/result.html

Case M, Ardiansyah F, Spector E (2007) Climate change in Indonesia. In: *South-East Asia's environmental future: the search for sustainability* (Issue January 2007)

Cox GW, Atkins MD (1979) Agricultural ecology–an analysis of world production systems. W. H. Freeman, 721p

Cruz R, Jafari M, Lal M (2007) Asia. In: Murdiyarso D, Nishioka S (eds) Asia. Climate change 2007: impacts, adaptation, and vulnerability (Issue March 2016). Cambridge University Press, Cambridge, pp 469–506. https://www.researchgate.net/publication/284683271_Asia_Climate_change_2007_Impacts_adaptation_and_vulnerability

Davenport TL (2003) Management of flowering in three tropical and subtropical fruit tree species. *HortScience 38*(7):1331–1335. https://doi.org/10.21273/hortsci.38.7.1331

Dulbari D, Santosa Yonny Koesmaryono Y, Sulistyono E, Wahyudi A, Herdhata A, Guntoro D (2021) AGRIVITA local adaptation to extreme weather and its implication on sustainable rice. AGRIVITA J Agric Sci 43(1):125–136. https://agrivita.ub.ac.id/index.php/agrivita/article/view/2338/1349

Fauzi AR, Junaedi A, Lubis I, Ghulamahdi M, Aswidinnoor H (2021) Relationship of size and shape rice seed to early seedling vigor traits. IOP Conf Ser Earth Environ Sci 694(1). https://doi.org/10.1088/1755-1315/694/1/012039

Forest Watch Indonesia (2002) The state of the forest. Indonesia. In: Matthews E (ed) Indonesia Bogor Indonesia Forest Watch Indonesia and Washington DC Global Forest Watch. http://pdf.wri.org/indoforest_full.pdf

Fujii K, Shibata M, Kitajima K, Ichie T, Kitayama K, Turner BL (2018) Plant–soil interactions maintain biodiversity and functions of tropical forest ecosystems. Ecol Res 33(1):149–160. https://doi.org/10.1007/s11284-017-1511-y

Gallery RE (2016) Ecology of tropical rain forests. In: Ecology and environment (Issue January 2014). Springer, Berlin, pp 247–272. https://doi.org/10.1007/978-1-4614-7501-9

Gray SB, Brady SM (2016) Plant developmental responses to climate change. Dev Biol 419(1):64–77. https://doi.org/10.1016/j.ydbio.2016.07.023

Hassanpour S, Maheri-Sis N, Eshratkhah B, Mehmandar FB (2011) Plants and secondary metabolites (Tannins): a review. Int J Forest Soil Erosion 1(1):47–53

Hatfield JL, Prueger JH (2015) Temperature extremes: effect on plant growth and development. Weather Climate Extremes 10:4–10. https://doi.org/10.1016/j.wace.2015.08.001

Herlina NFN, Aziz SA, Kurniawati A, Faridah DN (2017) Growth and production of Black Cumin (*Nigela sativa* L.) at three altitudes in Indonesia. *Indonesian Agron J 45*(3), 323–330. https://journal.ipb.ac.id/index.php/jurnalagronomi/article/view/13363

Isah T (2019) Stress and defense responses in plant secondary metabolites production. Biol Res 52(1):39. https://doi.org/10.1186/s40659-019-0246-3

Lasco RD, Boer R (2006) An Integrated assessment of climate change impacts, adaptations, and vulnerability in watershed areas and communities in Southeast Asia. a final report submitted to assessments of impacts and adaptations to climate change (AIACC), Project No. AS 21. In: The International START Secretariat, Washington, DC, USA, vol 2003. http://www.start.org/Projects/AIACC_Project/FinalReports/Final Reports/FinalRept_AIACC_AS21.pdf

Lawson T, Blatt MR (2014) Stomatal size, speed, and responsiveness impact on photosynthesis and water use efficiency 1 [C]. *Plant Physiol 164*(April 2014), 1556–1570. https://doi.org/10.1104/pp.114.237107

Lestari S, King A, Vincent C, Karoly D, Protat A (2019) Seasonal dependence of rainfall extremes in and around Jakarta, Indonesia. Weather Climate Extremes 24(Sept 2018):100202. https://doi.org/10.1016/j.wace.2019.100202

Lin D, Xiao M, Zhao J, Li Z, Xing B (2016) An overview of plant phenolic compounds and their importance in human nutrition and management of type 2 diabetes. Molecules 21(1374):19. https://doi.org/10.3390/molecules21101374

Lumingkewas A, Koesmaryono Y, Aziz SA, Impron (2015a) Modifikasi Iklim Mikro untuk Tanaman Soba (*Fagopyrum esculentum*) Sebagai Pangan Fungsional. Pangan 24(1):75–82

Lumingkewas A, Koesmaryono Y, Aziz SA, Impron (2015b) The influence of temperature on rutin concentration of buckwheat grains in humid tropic. Int J Sci Basic Appl Res (IJSBAR) 20(1):1–9. https://gssrr.org/index.php/JournalOfBasicAndApplied/article/view/3393/2099

Martono B (2011) Variability and Growth response and asiaticoside production of Asiatic Pennywort (*Centella asiatica* (L.) Urban) at different site elevations and shades. IPB University

Meteorology, Climatology, and Geophysics Council of Indonesia (2021) Climate analysis. https://www.bmkg.go.id/?lang=EN

Miller NA, Stillman JH (2012) Physiological optima and critical limits. Nat Educ Knowl 3(10):1. https://www.nature.com/scitable/knowledge/library/physiological-optima-and-critical-limits-45749376/#url

Montgomery K (2006) Variation in temperature with altitude and latitude. J Geogr 105(3):133–135. https://doi.org/10.1080/00221340608978675

Mori S, Jun-Ichi H, Tauhid YI, Yamanaka MD, Okamoto N, Murata F, Sakurai N, Hashiguchi H, Sribimawati T (2004) Diurnal land–sea rainfall peak migration over Sumatera Island, Indonesian Maritime Continent, observed by TRMM Satellite and Intensive Rawinsonde Soundings. Monthly Weather Rev 132(8):2021–2039. https://journals.ametsoc.org/view/journals/mwre/132/8/1520-0493_2004_132_2021_dlrpmo_2.0.co_2.xml#affiliation0

Mualim L (2012) Waterleaf production and quality with organic and inorganic fertilizer [IPB University]. https://repository.ipb.ac.id/bitstream/handle/123456789/61192/2012lmu.pdf?sequence=1&isAllowed=n

Mulyana E (1997) Curah Hujan di Indonesia. Jurnal Sains & Teknologi Modifikasi Cuaca 3(1):1–4. http://puslitbang.bmkg.go.id/jmg/index.php/jmg/article/download/130/123

Murray-Tortarolo G, Jaramillo VJ, Maass M, Friedlingstein P, Sitch S (2017) The decreasing range between dry- and wet-season precipitation over land and its effect on vegetation primary productivity. PLoS ONE 12(12):1–11. https://doi.org/10.1371/journal.pone.0190304

Naylor RL, Battisti DS, Vimont DJ, Falcon WP, Burke MB (2007) Assessing risks of climate variability and climate change for Indonesian rice agriculture. Proc Natl Acad Sci USA 104(19):7752–7757. https://doi.org/10.1073/pnas.0701825104

NIC (2009) Southeast Asia and Pacific Island: The impact of Climate Change to 2030. In *Joint Global Change Research Institute Battelle Memorial Institute, Pacific Northwest Division Scitor Corporation.* https://www.dni.gov/files/documents/climate2030_southeast_asia_pacific_islands.pdf

Nievola CC, Carvalho CP, Carvalho V, Rodrigues E (2017) Rapid responses of plants to temperature changes. Temperature 4(4):371–405. https://doi.org/10.1080/23328940.2017.1377812

Odum E, Barrett G (1971) Fundamentals of ecology. In: Introduction to cultural ecology. https://doi.org/10.4324/9781003135456-2
Van Oosterzee P (1997) Where worlds collide: the Wallace Line. Reed Books, Kew, Victoria, 234p. ISBN: 0730104702
Pagare S, Bhatia M, Tripathi N, Pagare S, Bansal YK (2015) Secondary metabolites of plants and their role : overview secondary metabolites of plants and their role. Curr Trends Biotechnol Pharm 9(3):293–304. https://www.researchgate.net/publication/283132113_Secondary_metabolites_of_plants_and_their_role_Overview
Payne TE, Edis R (2012) Radioactivity in the environment. In: Twining JR, Baxter M (eds) Tropical radioecology. Elsevier. https://books.google.co.id/books?id=v_FPpYPJ3qUC&pg=PA221&lpg=PA221&dq=Tropical+soils+are+more+strongly+weathered+and+have+less+nutrients+and+a+range+of+conditions+that+adversely+affect+growth+as+a+consequence+of+the+higher+temperatures+and,+in+some+areas
Peng S, Huang J, Sheehy JE, Laza RC, Visperas RM, Zhong X, Centeno GS, Khush GS, Cassman KG (2004) Rice yields decline with higher night temperatures from global warming. Proc Natl Acad Sci USA 101(27):9971–9975. https://doi.org/10.1073/pnas.0403720101
Putri F (2021) Bioactive compound characteristics, growth, and green shallots production at different altitudes, seasons, and fertilizer rates. Supervised [IPB University]. https://repository.ipb.ac.id/handle/123456789/106157?show=full
Quinto-mosquera H, Moreno-Hurtado F (2016) Precipitation effects on soil characteristics in tropical rain forests of the Chocó biogeographical region. Rev Fac Nac Agron Medellín 69(1):7813–7823. https://doi.org/10.15446/rfna.v69n1.54749
Rachman L, Hazra F, Hartono A, Hanudin E, Mulyanto B (2021) Formulation of soil quality index plus to support soil management in preventing soil degradation in dryland farming. IOP Conf Ser Earth Environ Sci 694:1–8. https://doi.org/10.1088/1755-1315/694/1/012057 (012057)
Ramadhan BC, Aziz SA, Ghulamahdi M (2015) Potential bioactive content of Kepel leaves (*Stelechocarpus burahol*). Bull Penelitian Tanaman Rempah Dan Obat 26(2):99. https://doi.org/10.21082/bullittro.v26n2.2015.99-108
Rao VR, Sthapit BR (2012) Tropical fruit tree species and climate change. In: Sthapit B, Rao VR, Sthapit S (eds) Biodiversity international. //efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2F; https://www.bioversityinternational.org%2Ffileadmin%2F_migrated%2Fuploads%2Ftx_news%2FTropical_fruit_tree_species_and_climate_change_1541.pdf&clen=1558842&chunk=true
Rasmusson LM, Gullström M, Gunnarsson PCB, George R (2019) Estimation of a whole plant Q10 to assess seagrass productivity during temperature shifts. Nature 9(12667):1–9. https://doi.org/10.1038/s41598-019-49184-z
Réblová Z (2012) Effect of temperature on the antioxidant activity of phenolic acids. Czech J Food Sci 30(2):171–177. https://www.agriculturejournals.cz/publicFiles/60247.pdf
Reddy AR, Rasineni GK, Raghavendra AS (2010) The impact of global elevated CO2 concentration on photosynthesis and plant productivity. Curr Sci 99(1):46–57. https://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=http%3A%2F%2F; https://www.indiaenvironmentportal.org.in%2Ffiles%2FThe%2520impact%2520of%2520global%2520elevated%2520CO2.pdf&clen=997343&chunk=true
Rintelen K Von, Arida E, Häuser C (2017) A review of biodiversity-related issues and challenges in megadiverse Indonesia and other Southeast Asian countries. Res Ideas Outcomes 3(e20860). https://doi.org/10.3897/rio.3.e20860
Román-Palacios C, Wiens JJ (2020) Recent responses to climate change reveal the drivers of species extinction and survival. In: Stenseth NC (ed) Proc Natl Acad Sci USA 117(8):4211–4217. https://doi.org/10.1073/pnas.1913007117

Roux X Le, Lacointe A, Escobar-gutiérrez A, Le S, Roux X Le, Lacointe A, Escobar-gutiérrez A, Carbon-based SLD (2001) Carbon-based models of individual tree growth : a critical appraisal To cite this version : HAL Id : hal-00884173 Carbon-based models of individual tree growth : a critical appraisal. Ann For Sci 58:469–506. https://hal.archives-ouvertes.fr/hal-00884173/document

Ruthenberg H (1971) Farming systems in the tropics. Clarendon Press. https://books.google.co.id/books/about/Farming_Systems_in_the_Tropics.html?id=2Z9FAQAAIAAJ&redir_esc=y

Scranton K, Amarasekare P (2017) Predicting phenological shifts in a changing climate. Proc Natl Acad Sci USA 114(50):13212–13217. https://doi.org/10.1073/pnas.1711221114

Shannon LM, Vellis J de, Lew J (1963) Malonic acid biosynthesis. Plant Physiol 38(6):691–697. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC549996/pdf/plntphys00422-0071.pdf

Sharma A, Shahzad B, Rehman A, Bhardwaj R, Landi M, Zheng B (2019) Response of phenylpropanoid pathway and the role of polyphenols in plants under abiotic stress. Molecules 24(13):1–22. https://doi.org/10.3390/molecules24132452

Siswanto S, Oldenborgh GJ Van, Nederlands K, Instituut M, Nederlands K, Instituut M, Nederlands K, Instituut M (2015) Temperature, extreme precipitation, and diurnal rainfall changes in the urbanized Jakarta city during the past 130 years. Int J Climatol 36. https://doi.org/10.1002/joc.4548

Smith NG, Dukes JS (2012) Plant respiration and photosynthesis in global-scale models: incorporating acclimation to temperature and. Glob Change Biol. https://doi.org/10.1111/j.1365-2486.2012.02797.x

Souvannakhoummane K (2014) The conservation of Zingiberaceae in Lao PDR. In: The 3rd Xishuangbanna international symposium on botanical gardens and climate, vol. 3. https://www.researchgate.net/publication/275346612_The_Conservation_of_Zingiberaceae_in_Lao_PDR

Spangenberg G (2014) Flavonoids: a metabolic network mediating plants adaptation to their real estate. Front Plant Sci 5:1–16. https://doi.org/10.3389/fpls.2014.00620

Sukara E (2014) Tropical forest biodiversity to provide food, health and energy solution of the rapid growth of modern society. Procedia Environ Sci 20:803–808. https://pdf.sciencedirectassets.com/270397/1-s2.0-S1878029614X00022/1-s2.0-S187802961400098X/main.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEB4aCXVzLWVhc3QtMSJIMEYCIQDwVh5frhzvn3YHgvvvT14NfUG56Ov6BCwOh1sFfR%2BY2wIhAN0sX%2FIQMRwF8ch8iBnY%2FS1pWvKnvXTkslT13z

Supari, Tangang F, Juneng L, Aldrian E (2017) Observed changes in extreme temperature and precipitation over Indonesia. Int J Climatol 37(4):1979–1997. https://doi.org/10.1002/joc.4829

Verma N, Shukla S (2015 Impact of various factors responsible for fluctuation in plant secondary metabolites. J Appl Res Med Aromat Plants 2:105–113. https://www.sciencedirect.com/science/article/pii/S2214786115300152?casa_token=NyOXBJcq9EoAAAAA:d6BFhG1sMGjcL2k8Q00PAGfDx9gl_e6ZOaPELrsqVIDIcQM8xu6DTPJzMJngYB6lPqjJGY-uoA--

Wang J, Xu J, Gong X, Yang M, Zhang C, Li M (2019) Biosynthesis, chemistry, and pharmacology of polyphenols from Chinese salvia species: a review. Molecules 24(155):1–23. https://doi.org/10.3390/molecules24010155

Winter K, Holtum JAM (2014) Facultative crassulacean acid metabolism (CAM) plants powerful tools for unraveling the functional elements of CAM photosynthesis. J Exp Bot 65(13):3425–3441. https://doi.org/10.1093/jxb/eru063

Wirnas D, Jaisyurahman U, Marwiyah S, Trikoesoemaningtyas, Purnamawati H, Sutjahjo SH (2020) Early generation selection for tolerance to high-temperature stress in rice. Indonesian Agron J 48(2):111–117. https://journal.ipb.ac.id/index.php/jurnalagronomi/article/view/30210/20527

Wright ST, Muller-Landau HC, Schipper J (2009) The future of tropical species on a warmer planet. Conserv Biol 23(6):1418–1426. https://conbio.onlinelibrary.wiley.com/doi/epdf/https://doi.org/10.1111/j.1523-1739.2009.01337.x

Yamanaka MD (2016) Physical climatology of Indonesian maritime continent: an outline to comprehend observational studies. Atmos Res 178–179:231–259. https://doi.org/10.1016/j.atmosres.2016.03.017

Yamori W, Hikosaka K, Way DA (2014) Temperature response of photosynthesis in C3, C4, and CAM plants: temperature acclimation and temperature adaptation. Photosynth Res 119(1–2):101–117. https://doi.org/10.1007/s11120-013-9874-6

Ye W, van Dijk AIJM, Huete A, Yebra M (2021) Global trends in vegetation seasonality in the GIMMS NDVI3g and their robustness. Int J Appl Earth Obs Geoinf 94:102238. https://doi.org/10.1016/j.jag.2020.102238

Zhang Y, Dong W, Zhao X, Song A, Guo K, Liu Z, Zhang L (2019) Transcriptomic analysis of differentially expressed genes and alternative splicing events associated with crassulacean acid metabolism in orchids. Horticultural Plant Journal 5(6):268–280. https://doi.org/10.1016/j.hpj.2019.12.001

Zhao J, Zhang Y, Song F, Xu Z, Xiao L (2013) Phenological response of tropical plants to regional climate change in xishuangbanna, south-western China. J Trop Ecol 29(2):161–172. https://doi.org/10.1017/S0266467413000114

Dr. Sandra Arifin Aziz was born in Jakarta, Indonesia, on October, 26th 1959. She works as a Professor at the Division of Plant Ecophysiology, Department of Agronomy and Horticulture, IPB University, Indonesia. She has also served as the Head of the Natural Resources and Plant Cultivation Division of Tropical Biopharmaca Research Center, IPB University. Her areas of research include agronomy, horticulture, medicinal plant, organic agriculture, and indigenous tropical plant species such as orchids. She published many books covering these areas such as: Herbal Medicine and Organic Phytopharmaceuticals, In Astuti D. A., Sudarsono, Sulaeman A., Syukur M. (eds.). Development of Organic Agriculture in Indonesia—Thoughts of Professors of IPB. pp. 247–264. IPB Press Publ. 2016; Rice and Other Organic Food Crops, In Astuti D. A., Sudarsono, Sulaeman A., Syukur M. (eds.) Development of Organic Agriculture in Indonesia—Thoughts of Professors of IPB. IPB Press Publ. pp. 203–218. 2016; Guava Leaf Phenolics and Flavonoids Production, Lambert Academic Publishing. 135 p. 2017; Technical Guidelines for Red Fruit Good Agriculture Practices (GAP). 94 p. Faculty of Agriculture, Bogor Agricultural University. 2017; Guidelines for Postharvest Handling (Good Handling Practices/GHP) of Red Fruit, Faculty of Agriculture, Bogor Agricultural University, 2017; Ecophysiological perspective in producing medicinal plant bioactive compound, In Andarwulan N. (ed.), Increasing Productivity, Utility, and Sustainability of Indonesian Plant Biodiversity, Vol.1: 427–472. IPB Press Publ.

Effects of Climate Change on Insect Pollinators and Implications for Food Security — Evidence and Recommended Actions

Rachid Sabbahi

Abstract Pollinators are crucial to biodiversity conservation, ecosystem protection, agriculture, and climate change adaptation. Crop pollination has a global annual value of US $235–577 billion. In Morocco, insect pollinators contributed USD $1235.06 M to main crop production, accounting for 8.52% of total agricultural GDP. In response to climate change, the geographical range and phenology of insect pollinators shift, their interactions with plants and other taxa are altered, and in some cases, pollination services are reduced. As a result, a decrease in pollination activity clearly compromises adequate crop production for a growing human population. Consequently, other plant species that rely on insect pollinators for outcrossing may also face extinction, putting human health and crop production at risk. The effects of elevated temperature on flowering plants and insect pollinators may have an impact on pollinator floral resources and plant pollination success, respectively. Plant reactions to global warming, irregular rainfall, and other environmental conditions may include altered blooming, nectar, and pollen production, as well as changes in floral resource availability, distribution, visitation quality, pollinator reproductive output, and threat from insect pests and diseases. Pollinator responses, such as changes in foraging spatial scale, body size, and lifetime, may also influence pollen flow patterns and pollination efficiency. Climate change must be considered because it has the potential to have a substantial influence on pollinator populations, resulting in lower productivity and imperiling food security. Efforts should therefore be directed toward the preservation of pollinators. One solution for improving agriculture in Morocco and rising its resilience to climate change is to take an integrated agroecological and socioeconomic approach to pollinator conservation. Thus, monitoring the status and trends of insect pollinators and assessing pollination functions and services are needed to address the potential effects of climate change and inform adaptive management of ecosystems that could help ensure food security and agricultural sustainability. Recommended actions include as well doing more research to fill knowledge gaps, expanding studies to cover a wider range of pollinators, and promoting coordinated follow-up work at the local, regional, and national levels.

R. Sabbahi (✉)
Laboratory of Plant Biotechnology, Higher School of Technology, University of Ibn Zohr of Agadir, Laayoune, Morocco
e-mail: r.sabbahi@uiz.ac.ma

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_8

Keywords Agriculture · Climate change · Economic value · Ecosystem services · Food security · Insect pollinators · Pollination

1 Introduction

Alleviating poverty and achieving food security in the face of global climate change and spiraling input costs, as seen in recent years, would be a major challenge in coming decades, thus endangering human health and development (Feulner 2017; Mugambiwa and Tirivangasi 2017). Climate change is one of the most serious threats confronting Africa's developing countries, where agriculture plays a significant role in the economy (Collier et al. 2008; Radhouane 2013). The increase in temperature and decrease in annual precipitation reduce the area of land suitable for agriculture, shorten the growing season, diminish crop yields, and threaten food security (Ait El Mokhtar et al. 2022). Its effects are likely to have a negative impact on biodiversity, agriculture, water management, food security, and livelihoods (Misra 2014; Connolly-Boutin and Smit 2016; Ofori et al. 2021).

The agriculture sector plays a major role in Morocco's social security and overall economic welfare (Ouraich et al. 2019). In terms of socioeconomic impacts, acute yield decreases may have serious repercussions for economic growth and poverty alleviation, given that this country relies substantially on the agricultural sector as a source of national income, through cash crop exports, and as a major supplier of employment opportunities, particularly in rural areas (Ouraich and Tyner 2015).

Morocco is a water-stressed country that is vulnerable to the impacts of climate change (UNESCO 2004; Ouraich et al. 2019). Weather and climate change have a direct influence on agricultural productivity (Arora 2019). Morocco is experiencing significant climatic variations, from both natural and man-made, as a result of large-scale deforestation, urbanization, and pollution, all of which are contributing to the country's rising tendencies (Karmaoui and Zerouali 2019). Climate change, water stress, habitat degradation, and resource fragmentation can all lead to changes in insect population dynamics and are new concerns for the country. Changes in temperature, precipitation, and atmospheric carbon dioxide concentration are all projected to have a substantial influence on crop growth (Zhang et al. 2021).

Insects are a dominant component of agricultural ecosystems and affect crop production in diverse ways, ranging from beneficial to adverse, and thus, fluctuations in insect populations should be of primary interest to both researchers and growers (Saunders et al. 2016). Environmental factors like temperature, humidity, and rainfall influence the population densities and result in seasonal fluctuations that could have a positive or negative impact on the populations of most insect species (Rafferty 2017; Halsch et al. 2021; Filazzola et al. 2021).

Over the last ten years, the international community becomes more conscious of the value of pollinating insects as an integral component of agricultural diversity, on which human survival depends. Unfortunately, they are commonly exposed to multiple stressors through ecological interactions with their environments, and signs of a potentially severe decline in their populations are accumulating (Belsky and Joshi 2019; Hanberry et al. 2020). Better pollinator conservation and management are critical for health, nutrition, and food security, but also for sustaining and improving horticultural, seed, and fodder crop yields (Garratt et al. 2014).

The purpose of this chapter is to investigate the role of insect pollinators in food production and look at the evidence that their loss is threatening human food security and ecosystem resilience. This chapter will also discuss the threats and risks that pollinators face, as well as strategies for preventing the loss of pollinator services to food and agriculture.

2 Morocco's Climate Context

Morocco, with its arid and semi-arid climate, is one of the most vulnerable countries to the effects of climate change (Mohammed et al. 2020). Since the 1960s, mean annual temperatures have risen by 0.9 °C, with observed average increases of 0.2 °C per decade, exceeding the global average. Furthermore, the number of 'hot' days has increased substantially throughout all seasons. By 2060, the average annual temperature is expected to rise from 1.1 to 3.5 °C (Fig. 1). The projected rate of warming in the interior is faster than in the coastal regions.

Precipitation trends are highly variable in Morocco. Furthermore, seasonal rainfall patterns have moved to longer and more severe rain events in October and November, causing floods, but with considerable declines in rainfall during the rest of the year. Extreme weather phenomena, such as flooding in some regions, as well as droughts and heat waves in others, have become more common and intense.

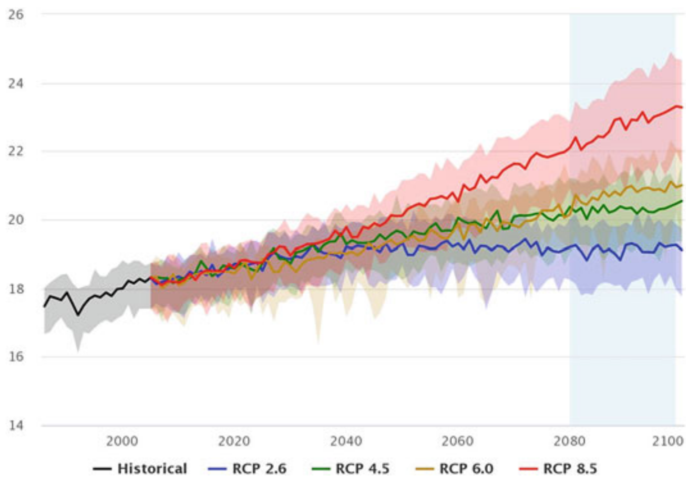


Fig. 1 Morocco's historical and forecasted average temperatures from 1986 to 2099. RCP: Representative Concentration Pathway. *Source* CCKP (2021)

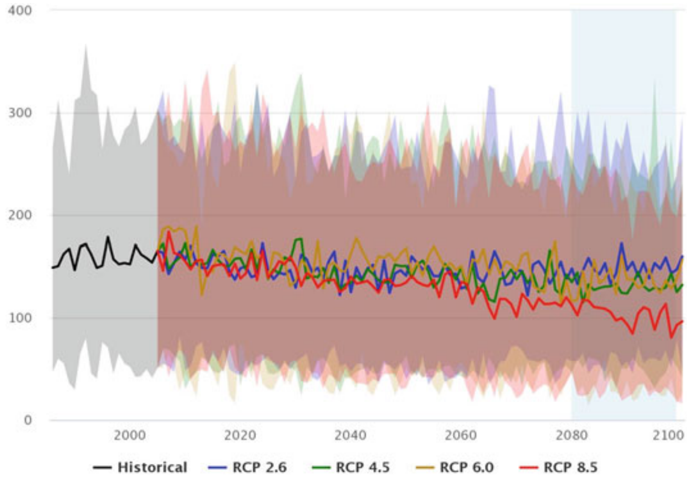


Fig. 2 Morocco's annual average precipitation from 1986 to 2099. RCP: Representative Concentration Pathway. *Source* CCKP (2021)

The average annual precipitation is expected to fall by 17% by 2050 (Fig. 2). Droughts are becoming more frequent, severe, and long-lasting (Schilling et al. 2020), which will have a negative impact on rural livelihoods, agroecological systems as well as the national economy as a whole. Extreme droughts have devastating consequences in arid and semi-arid climates in developing countries, where human livelihoods rely heavily on rainfed crops (Elkouk et al. 2021).

In Morocco, rising temperatures and shifting precipitation patterns will present new challenges for water resource availability, agricultural and livestock productivity, and population growth (Rochdane et al. 2014). In turn, this has resulted in social and ecological transformations, which could be described in the Moroccan context as change processes to deal with natural disasters and the repercussions of climate change in order to develop resilience (Kmoch et al. 2018). Thus, given the critical importance of meteorological data and information, they should be improved for regional climate modeling and climate change forecasts along with the development and adaptation of appropriate measures to deal with these changes in climate.

3 Crop Production in Morocco

Agriculture has always been a critical component for Morocco's socioeconomic growth. It is the primary sector of employment in Morocco—40% of the national workforce and 74% in rural regions (Abdelmajid et al. 2021)—and its contribution to GDP varies from 12 to 19% depending on the year's rainfall (Belcaid and El Ghini 2019). Moreover, 40% of Moroccans live in rural regions and make their livelihood via agriculture, either directly or indirectly (Ghanem 2015).

Morocco's arable land area is estimated to be 8.4 million ha, accounting for nearly 18.8% of total land area, with rainfed agriculture accounting for more than 80%. The agricultural property structure is defined by the existence of both small and large-scale farms. Farm holdings are often small (<5 ha) and typically in scattered parcels, accounting for 70% of all farms (EL Gharous and Boulal 2016).

Cereals are the primary crops in Morocco, accounting for nearly 43% of arable land. Despite the fact that cereal production continues to predominate, horticulture and livestock production are becoming more popular. In contrast to the historical expansion of cereal production, the expansion of vegetable and fruit production is primarily due to a rise in cultivable land, rather than an increase in yields.

Horticultural products account for more than 20% of agricultural exports in developing countries, or more than twice as much as cereal products (Lumpkin et al. 2005). Increasing agricultural exports is one of Morocco's primary governmental objectives. These exports comprise 2.80 M tons and have a monetary value of US $3185.82 M (average over the five-year period 2015–2019) (Sabbahi 2021). Citrus fruit (e.g., oranges, tangerines, and lemons), vegetables (e.g., tomato, green bean, and pepper), olive oil, almonds, table olives, and more recently, blueberries, cherries, and asparagus are among the most prominent agricultural exports. While the country's economic growth overall has grown more robust, agriculture remains climate-dependent, and hence very susceptible to changes in climate. The repercussions of a fall in Moroccan agricultural production would affect everyone from small-scale farmers to large-scale producers.

Climate change will be one of the most major threats to agriculture in the next years, and crop production in Morocco is expected to suffer as a result (Ouraich et al. 2019). Temperature is one of the most important climatological parameters during the vegetative growth and grain formation periods of crops (Moore et al. 2021). Aside from the long-term consequences of climate change, forecast models imply that extreme weather occurrences in Morocco will become much more frequent and severe (Filahi et al. 2017; El Alaoui El Fels et al. 2020; Hadri et al. 2020). The rising acknowledgment of climatic extremes as drivers of current and future ecological dynamics has increased interest in understanding these locally and internationally significant phenomena.

4 Pollinators, Pollination, and Food Production

4.1 Role of Pollinators

Pollination is the act of transferring pollen grains from one flower to another and is essential for the production of both seeds and fruits (Ollerton et al. 2011). Pollinators are agents that transport pollen from anthers to the stigmas of flowers, resulting in pollination. Agents include various animals such as bees, wasps, butterflies, moths, beetles, flies, birds, and bats. Insect pollinators are a diverse and abundant group of species that have coevolved with plants to form biodiverse and productive landscapes that support ecosystem services (de Lima et al. 2020; Salzman et al. 2021).

Morocco is recognized for its biodiversity, with a bee fauna of 961 species from six families and 68 genera, ranking the country fifth among the richest countries in the Mediterranean Basin. Eight percent (81 species) are Moroccan single-country endemics (Fig. 3) (Lhomme et al. 2020). Moroccan bee species richness is nearly half that of European bee diversity, despite the fact that Morocco's surface area accounts for only 7% of European surface area.

Pollinators provide numerous benefits to society, according to the Global Pollinator Assessment (IPBES 2016), by covering pollination of both crops and wild plants, contributing to long-term food and seed production, maintaining plant genetic diversity, foraging resources, and the conservation of biodiversity. One out of every three bites of food consumed is from pollinated plants, and the visitation of flowers by insects results in a plethora of raw materials and natural products of use to humans. Pollinators keep the global ecosystems running and are beneficial or required for nearly 80% of the crops grown around the world (Ollerton et al. 2011). Pollinators do, in fact, play a key role in 70% of important food crops to varied degrees (Klein et al. 2007). In Europe, 84% of crop species are largely reliant on insect pollination, notably honeybees (Williams 1994). Insect pollination is critical for entomophilous agricultural crops (McGregor 1976; Free 1993) and highly beneficial for self-fertile crops like cucumber, strawberry, raspberry, and canola (Chagnon et al. 1993; Gingras

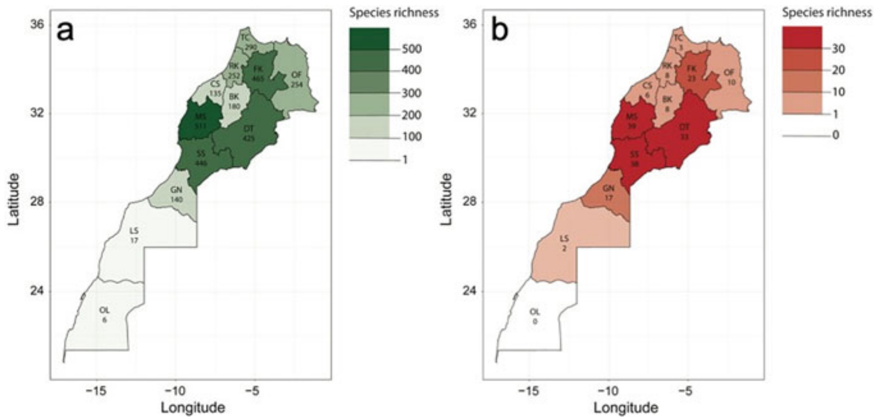


Fig. 3 Maps of Morocco showing regions colored by their known **(a)** bee species richness and **(b)** endemic bee species richness. Regions: Béni Mellal-khénifra (BK), Casablanca-Settat (CS), Dakhla-Oued Ed-Dahab (OL), Drâa-Tafilalet (DT), Fès-Meknès (FK), Guelmim-Oued Noun (GN), Laâyoune-Sakia El Hamra (LS), Marrakesh-Safi (MS), Oriental (OF), Rabat-Salé-Kénitra (RK), Souss-Massa (SS), Tanger-Tetouan-Al Hoceima (TC). *Source* Lhomme et al. (2020)

et al. 1999; Sabbahi et al. 2005; Chen et al. 2021). When crops are pollinated appropriately, agricultural production may be both superior in quality and quantity (Sabbahi et al. 2006; Petersen et al. 2013; Stein et al. 2017).

Even though many production areas in Morocco are pollinator-independent (e.g., cereal crops occupy 75% of arable land) and wind-pollinated, a great portion of vegetable and fruit crops are potentially vulnerable to pollinator decline and are mostly concentrated in three regions (Rabat-Salé, Fès-Meknès, and Souss-Massa). For example, the Fès-Meknès region accounts for roughly 38% of Moroccan apple production (681,558 tons per year) and 34% of the country's cultivated land (48,739 ha) (Moinina et al. 2018). The Souss-Massa region is the national leader in tomato production, with a cultivated land of 6635 ha (67% of total cultivated area) and an annual yield of over 902,400 tons (42% of total production).

4.2 Economic Value of Insect Pollination

Agriculture's dependence on pollinators has actually increased by 400% since the 1960s, with the worldwide economic value of crop pollination estimated to be US $235–577 B annually, which represents about 10% of the global crop market (Potts et al. 2016). Changes in crop production without these biotic pollinating services might boost consumer prices while costing farmers roughly US $2 B each year (IPBES 2016). Overall, insect pollinators impact 68.57% of Morocco's main crops. These crops cover 10.31% of total cropland, produce 27.28% of total crop yield, and generate 39.08% of total crop value (Sabbahi 2021). Insect pollination contributed USD $1235.06 M to Morocco's major crop production (Table 1), representing 8.52% of the overall agricultural GDP.

Table 1 Economic valuation of insect pollinators for main crops in Morocco

Crop category	Average value per ton (US $)	Total value of crop (US $ M)	Economic value of insect pollination (US $ M)	Vulnerability ratio (%)	Consumer surplus loss with elasticity (US $ M)	
					−0.5	−1.5
Fruit	434.31	1937.68	595.03	30.71	3135.36	524.64
Oilseeds	548.57	814.55	6.40	0.79	16.08	4.59
Pulses	657.30	220.83	14.30	6.48	35.80	10.24
Spices	2092.05	52.21	2.61	5.00	5.50	1.77
Tree nuts	2956.03	323.26	210.12	65.00	1200.68	190.90
Vegetables	264.04	1200.68	406.60	33.86	15,233.48	524.41
Total		4549.20	1235.06	27.15	19,626.89	1256.54

Source Sabbahi (2021)

Any evaluation of pollination services must take into account both the consumer and producer perspectives. Although pollination is generally thought to be of interest to farmers, it is important not to overlook the consumers. An economic analysis of pollinator shortages has led to the conclusion that consumers of a product exposed to a pollinator shortage may suffer as the product becomes scarcer and more expensive (Kevan and Phillips 2001). The scarcity of pollinators may thus result in an increase in the price of commercially available products for consumers.

In terms of social welfare, the immediate impact of pollinator decline would be a decrease in yield while maintaining the same input and effort. This would suggest that crop production costs per unit would increase, causing a reduction in consumer surplus loss (CSL). The CSL for Morocco's main crops varies from US \$19,626.89 M to US \$1256.54 M, with average price elasticity values of −0.5 and −1.5, respectively (Table 1). In the case of pollination services loss, this price interval on the CSL shows the difference between what Moroccan consumers are willing to pay for the ecosystem services in relation to its market price (Picanço et al. 2017). If natural pollinators decline, crop yield and farmer surpluses would suffer severely. If farmers must switch to new crops, it should be assessed if these crops result in reduced consumer demand and net income for the farmer or whether the switch incurs costs (e.g., storage facilities, new processing, etc.) (Brookes and Barfoot 2017).

Pollinator-dependent crops contributed for 1.71 M tons (60.94%) of agricultural exports, amounting US \$1604.43 M (50.36%), and insect pollination accounts for 27.15% of overall agricultural yield when the major crops are considered (Sabbahi 2021). As a result, because crop production is dependent on pollinator activity, insect pollinators offer valuable ecological services to farmers.

4.3 Pollinators for Food Security

Food security will be jeopardized as a consequence of the predicted effects of global climate change and extreme weather on agriculture and fisheries (Gomez-Zavaglia et al. 2020). Climate change has already influenced the crop suitability in several areas, causing variations in production levels for major crops. Crop production is being harmed as a result of a rise in both direct and indirect climatic extremes (e.g., heat stress, drought, changes in rainfall extremes, flood damage, spread of insect pests and diseases, etc.) (Raza et al. 2019).

Nearly two-thirds of the crops that feed the world's population rely on insect pollination. In a world without pollinators, foods like nuts, fruits, and vegetables would become scarce and costly. Garibaldi et al. (2016) have revealed that insect pollinator deficits now account for a considerable proportion of crop yield shortages, even after accounting for other important environmental and agronomic variables (such as the level of intensification and the level of crop dependence on insect pollination). In plots smaller than 2 ha, for example, insect pollinator abundance alone contributed to an average of 31% of the yield deficit. Researchers discovered a similar productivity gain when pollinator fauna is diverse in larger plots where pollinator fauna diversity is often lower due to a large predominance of honeybees. However, when this diversity is low, the productivity gain is nil, so that when both the number and diversity of pollinating insects are increased, crop yields increase by more than 20% on a global scale. As a result, these findings highlight the global impact of a decline in pollinating insect populations on crop yields.

A future with compromised pollination due to a lack of insect pollinators indicates a greater need for hand pollination methods (Allsopp et al. 2008), but the labor costs associated with these methods can be exorbitant to smallholder farmers (Wurz et al. 2021). This projected increase in food production costs will lead to a rise in food prices, potentially culminating in a new kind of food elitism, in which only those who can afford to pay the rising cost of food will be able to consume it (Marshman et al. 2019).

Insect pollinator-dependent crops provide human cultures with a diverse diet and high levels of micronutrients (vitamin A, iron, folate) that are needed for human health (IPBES 2016). Entomophilous crops, for example, provide 70% of vitamin A intake (Eilers et al. 2011). Micronutrient deficits can impede people from thriving and have long-term health consequences (Ellis et al. 2015). As a result, losses in pollinator populations may result in a considerable increase in preventable diseases associated with healthy diets.

Pollinators are regarded as keystone species because they will boost smallholder farmers' revenues and ensure consumer food security while at the same time helping to conserve biodiversity and the environment (Kevan 1999; Tibesigwa et al. 2019; Christmann et al. 2021a). However, according to several studies, the number of pollinators is already in a sharp decline in many parts of the globe (van Engelsdorp et al. 2008; Potts et al. 2016; Powney et al. 2019). Not only are rising temperatures linked to climate change (Settele et al. 2016; Filazzola et al. 2021), but also resource fragmentation and habitat loss, monoculture farming, intensive agricultural practices, insect pests and diseases, and overuse of agricultural chemicals (Sabbahi et al. 2009; Vanbergen and the Insect Pollinators Initiative 2013; Goulson et al. 2015; Dicks et al. 2021). If current trends continue, nutritious food like vegetables, fruits, and pulses will be replaced by staple crops such as rice, potatoes, and maize, thereby promoting unbalanced diets (Nicholson et al. 2021).

5 Climate Change Impacts on Insect Pollinators

5.1 Pollinator Decline

Pollinators require a wide range of resources in their environment in order to feed, nidify, reproduce, and protect themselves. The loss of any of these resources may result in severe declines or local extinctions of pollinators. According to Sánchez-Bayo and Wyckhuys (2019), insects are threatened by global extinction, which could lead to a catastrophic collapse of natural ecosystems. This meta-analysis found that

41% of insect species are declining in the last 10 years, and a third are threatened with extinction, based on an analysis of 73 studies from around the world. Insect populations are declining at a rate eight times faster than mammals, birds, and reptiles. Thus, insect populations have declined by 2.5% per year on average over the last 30 years: at this rate, scientists are concerned that insects will become extinct within a century.

Insect extinction would have a devastating effect on ecosystems (Cardoso et al. 2020). When pollinators decline, the plants that they depend on, the services they provide, and the productivity of ecosystems follow this trend (Hegland et al. 2009). Birds, reptiles, amphibians, and other fish that rely on them for food would undoubtedly be endangered (Goulson 2019). Figure 4 looks more closely at which insect species are declining the most. Thus, over the last decade, more than half of the populations of butterflies and Trichoptera (related to butterflies) have disappeared. The 10-year extinction rate for bees and beetles (scarabs, ladybirds) is close to 50%, while dragonflies' numbers have dropped by 35% and a quarter of Diptera (flies) have vanished.

Climate change is a looming threat, impacting both insect pollinators directly, and changing the floral ecosystems these species depend on. Changes in richness and diversity, range changes and restrictions, changes in flight periods, as well as asynchrony between coevolved pollinators and plants, are the primary concerns as the climate changes. Nonetheless, it is extremely difficult to attribute insect declines to global warming alone, and there is an emerging understanding that the interaction between climate change with other global change stressors, such as habitat change, pollution, and a variety of biological factors, is currently impacting insect pollinators (Potts et al. 2010; Dicks et al. 2021).

According to regional and national assessments, climate change poses a significant threat to some insect pollinators. It has undoubtedly limited the range of some stoneflies, bumblebees, and damselflies that are acclimated to colder temperatures and

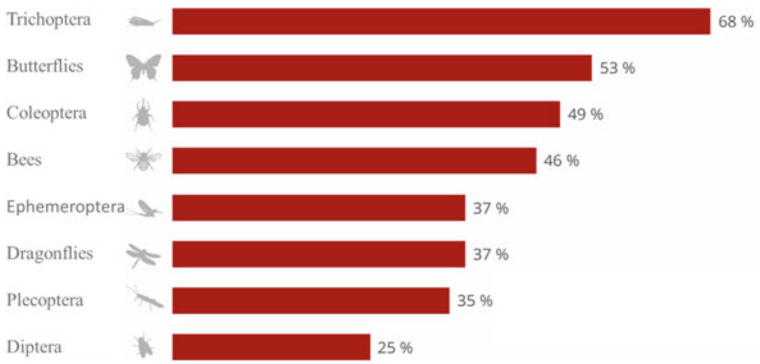


Fig. 4 Insect populations decline over the last decade. Figures derived from an analysis of 73 studies, the majority of which came from North America and Europe, with some from Australia, China, and South Africa. *Source* Adapted from Sánchez-Bayo and Wyckhuys (2019)

higher latitudes (Sheldon 2012; Ball-Damerow et al. 2014; Soroye et al. 2020), as well as adversely affected some mountainous insect species (Halsch et al. 2021). Environmental factors (e.g., temperature, water availability, and humidity) are expected to impact pollinator and plant phenology, as well as their spatial distribution along altitude and latitude gradients (Herrando et al. 2019). Such changes have the potential to modify the structure of these two types of communities and disturb their mutualistic interactions, resulting in local extinctions. The altitude and latitude at which some insect pollinators and plants have been observed to change over the last 30 years, presumably due to climate change (Walther 2003). For example, butterfly species from the USA, Great Britain, Norway, and Spain have changed their abundance, ranges, and seasonal activities in recent decades, while shifts in habitat caused by climate change have had substantial effects on the populations and global distribution of many other pollinator species (Hill et al. 1999; Klanderud and Birks 2003; Stewart et al. 2020; Halsch et al. 2021).

5.2 Pollination and Ecosystem Functions

Changes in climatic patterns driven by global warming are influencing plant phenology, geographic distribution, and pollinators may struggle to adjust their foraging activities in response to the altered anthesis timing (Murcia 1990; Descamps et al. 2018; Gérard et al. 2020). Climate change, according to Memmott et al. (2004), has the potential to disrupt pollinators' temporal overlap with their floral food resources in the absence of compensatory mechanisms. Furthermore, because of climate change, crops may be shifted to more suitable areas, but most pollinators would be unable to adapt, resulting in a decreased pollination (Biesmeijer 2006; Giannini et al. 2017; Imbach et al. 2017).

Climate change also alters the growing season, causing plants to bloom earlier in the season. As a result, gaps in the needed constant availability of nectar and pollen throughout the foraging season of bees might occur (van der Sluijs and Vaage 2016). Peñuelas et al. (2002) investigated the long-term biological cycles of Mediterranean plants and pollinators and revealed that there are differences in plant phenological development (leaf fall, flowering, and fruiting). According to the authors, these differences, which were not synchronized with observed changes in butterfly emergence and migratory bird arrival dates, have the potential to alter the structure and function of healthy ecosystems.

The potential for species–species relationships to be decoupled as a result of different phenological responses to climate change has long been recognized, for example, for flowering plants and their insect pollinators (Burkle et al. 2013; Settele et al. 2016). A direct effect on species phenology and distribution causes spatial and temporal mismatches disrupting plant–pollinator ecological interactions (Hegland et al. 2009). If the distribution and blooming period of flowering plants change in response to climate change, then the spatial distribution of pollinators and the timing of their nectar need to change as well (Kudo and Ida 2013). This can lead to

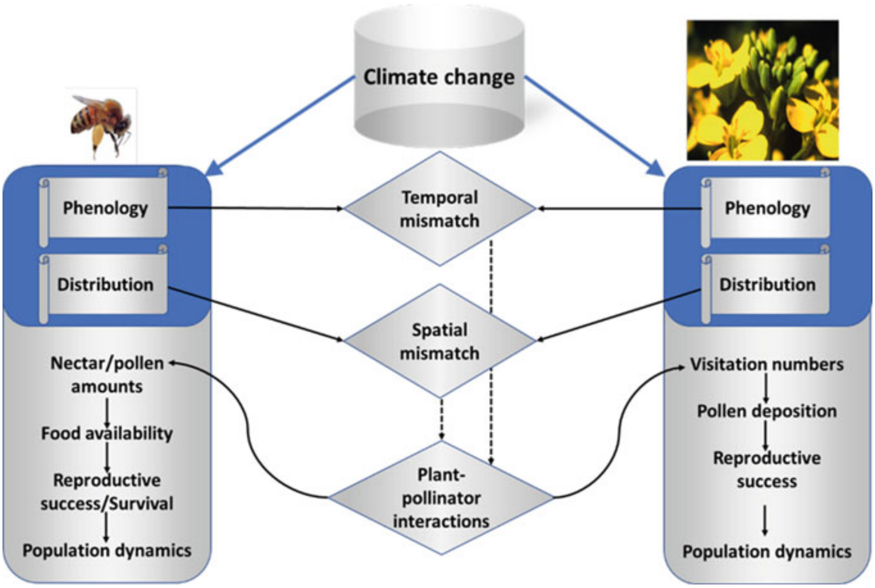


Fig. 5 Climate change impact on plant-pollinator interactions. *Source* Modified from Hegland et al. (2009)

pollinators not having enough nectar resources when they need them. This mismatch can have cascade effects on the ecosystem function (Fig. 5), especially for plants and pollinators with specialized relationships.

According to Bezerra et al. (2019), climate change threatens the production of passion fruit in the Neotropics by reducing agricultural land and the abundance of the two major pollinator bee species (*Xylocopa frontalis* and *X. grisescens*). Climate change may have an effect on favorable areas for *Xylocopa* bees and passion fruit crops. In such cases, there could be a 64% loss in cultivating areas for passion fruit, and pollinator-passion fruit mismatch might exceed 54%, threatening crop production and increasing the potential spatial mismatch between the crop and its pollinators.

On a global scale, pollination services may face significant stress, with the developing world feeling more pressure than the developed world, and tropical regions feeling more pressure than temperate regions (Ollerton et al. 2011). If these services were not provided, many species and interdependent processes in an ecosystem would become extinct. To ensure high production and global food security, green strategies and policies for pollinator conservation, restoration, and augmentation must be formulated and implemented to protect pollinators from the true havoc of climate change, which cannot be slowed but only its effects can be mitigated. Furthermore, pollinator conservation entails raising awareness of the fact that not only species but also interspecies interactions must be the subject of conservation measures and careful management in order to strengthen the essential links that exist within the ecosystem (Simmons et al. 2020).

6 Pollinators Adaptation to Climate Change

Long-term effects of climate change on pollinators and pollination services to agriculture may not be fully apparent for many decades due to a delayed response in ecological systems. With global food demand rising, we simply cannot afford to wait until crop yields begin to decline before taking action to protect insect pollinators (Goulson et al. 2015). One of the possibilities for enhancing agriculture and boosting its resilience to climate change is to use integrated agroecological strategies to conserve pollinators (Henríquez-Piskulich et al. 2021). Actions to support pollinators and pollination could be implemented by: (i) promoting pollinator-friendly habitats; (ii) improving the management of pollinators, and reducing risk from pests, invasive species, and pathogens; (iii) reducing risk from chemical pesticides; (iv) enabling pollinator-friendly policies, practices, and instruments; and (v) conducting research, monitoring, and assessment (IPBES 2016). Unfortunately, the efficacy of adaptation efforts in ensuring pollination in the face of climate change is still untested (Vasiliev and Greenwood 2021).

Pollinators' adaptation will be heavily influenced by the reconfiguration or expansion of their geographic distribution in response to changing climate conditions (Hegland et al. 2009). Plant production is greatest when a broad mix of pollinators, including but not limited to managed bees, is present. Different pollinators are at work depending on the time of day or weather conditions, and the most frequent and efficient pollinators of a plant might change from year to year (Kremen et al. 2002). Then, a diversified assemblage of pollinators with varying features and sensitivities to environmental conditions is one of the finest allies for mitigating climate change concerns.

Small modifications in restoration practices can boost the efficacy in supporting pollinators and local ecosystems, while also generating long-term impacts. Connecting and sensitizing farmers to sustainable technology and activities are critical because they can make a significant contribution to achieving ecological goals (Arora 2019). Farming and subsistence systems usually rely on farm practices that encourage a high level of diversity and can serve as the foundation for creating a more sustainable agricultural growth model (Kremen et al. 2012). Taking into account the seasonal availability of pollinator-required resources and preserving natural habitat connectivity in farming areas are two examples of how farming communities might effectively adapt to the impacts of climate change on pollinators (Burkle et al. 2013).

As species move across the landscape and exploit different habitats, increased connectivity between environmentally friendly managed and protected areas is required to: (i) enhance spillover of ecosystem service providers from land-sharing/-sparing measures to agricultural production and save service-providing species from extinction in contested areas; (ii) enable immigration and counteract potential extinctions in spared habitats; and (iii) conserve response diversity of species communities for ensuring resilience of ecosystem services in changing environments (Grass et al. 2019). Current land-sharing practices range from the local (e.g., wildflower strips) to the field (e.g., organic farming) to the landscape scale (e.g., diversified farming systems) (Grass et al. 2021).

Many high-income countries provide financial support to farmers to plant wildflower strips beside crops to attract pollinating insects (McCracken et al. 2015). These costly practices, however, may be unsustainable for low- and middle-income countries (Christmann et al. 2017). An alternative program 'Farming with Alternative Pollinators' has been established in Morocco since 2015, with the main goals of ensuring pollinator diversity, boosting crop yields over the long term, increasing producer's net income, and enhancing national policies for agricultural development (Christmann et al. 2017). Instead of wildflowers, which many farmers regard as weeds that take up valuable acreage, the strips are planted with marketable plants such as oilseeds, spices, vegetables, or medicinal plants in between their crops to attract wild pollinators and natural enemies of crop pests, while also providing an extra income source for farmers (Christmann et al. 2021b).

Morocco joined the 'Coalition of the Willing on Pollinators' in May 2019 and is now working on a national pollinator strategy and action plan. Unfortunately, there is a dearth of data on ongoing and long-term changes in pollinator populations, and decision-makers do not yet have precise information on pollinator declines to deal with future pressures and threats associated with climate change. Only a single systematic insect monitoring program exists—the European Butterfly Monitoring Scheme (Warren et al. 2021). This emphasizes the significance of ongoing monitoring of pollinator status, as well as pollination functions and services, in order to guide adaptive management of natural ecosystems (Sabbahi 2021). Monitoring the abundance and diversity of wild pollinators in agricultural landscapes could be an important first step in building an evidence-based strategy to conserve pollinators. A good knowledge of Moroccan pollinator fauna will support the selection of appropriate foraging and nesting resources for pollinators, enabling the establishment or safeguarding of pollinator habitats. Relevant actions in this regard include undertaking more research to bridge knowledge gaps, broadening studies to include a wide range of pollinators, and promoting collaborative efforts at the local, national, and international levels.

7 Conclusion

Climate change is one of the agriculture's key driving forces. Climate-smart agriculture should then include management practices capable of producing a wide range of climatic conditions while sustaining or improving animal, plant, and soil health. Within this broader framework, insect pollinators merit special attention due to their critical ecosystem function and vital role in guaranteeing food production and human well-being. An integrated approach that tackles the multiple stressors at the same time is required in order to reverse pollinator loss and maintain a stable equilibrium that guarantees global food security and ecosystem integrity in the future. Hence, immediate actions at the national and international levels to understand and combat climate change should become a priority. Adaptation and mitigation strategies are needed, which would include research reorientation and substantial policy interventions. Regional and global collaboration would be a great asset in resolving these concerns as well as in developing institutional and human resource capacities, which are the two pillars of sustainable agriculture.

References

Abdelmajid S, Mukhtar A, Baig MB, Reed MR (2021) Climate change, agricultural policy and food security in Morocco. In: Behnassi M, Barjees Baig M, El Haiba M, Reed MR (eds) Emerging challenges to food production and security in Asia, Middle East, and Africa: climate risks and resource scarcity. Springer International Publishing, Cham, pp 171–196

Ait El Mokhtar M, Anli M, Ben Laouane R et al (2022) Food security and climate change. In: Information Resources Management Association (ed) Research anthology on environmental and societal impacts of climate change. IGI Global, pp 44–63. https://doi.org/10.4018/978-1-6684-3686-8.ch003

Allsopp MH, de Lange WJ, Veldtman R (2008) Valuing insect pollination services with cost of replacement. PLoS ONE 3:e3128. https://doi.org/10.1371/journal.pone.0003128

Arora NK (2019) Impact of climate change on agriculture production and its sustainable solutions. Environ Sustain 2:95–96. https://doi.org/10.1007/s42398-019-00078-w

Ball-Damerow JE, M'Gonigle LK, Resh VH (2014) Changes in occurrence, richness, and biological traits of dragonflies and damselflies (Odonata) in California and Nevada over the past century. Biodivers Conserv 23:2107–2126. https://doi.org/10.1007/s10531-014-0707-5

Belcaid K, El Ghini A (2019) Measuring the weather variability effects on the agricultural sector in Morocco. In: Proceedings of the thirteenth international conference on management science and engineering management. Springer, Cham, pp 70–84

Belsky J, Joshi NK (2019) Impact of biotic and abiotic stressors on managed and feral bees. Insects 10:233. https://doi.org/10.3390/insects10080233

Bezerra ADM, Pacheco Filho AJS, Bomfim IGA et al (2019) Agricultural area losses and pollinator mismatch due to climate changes endanger passion fruit production in the Neotropics. Agric Syst 169:49–57. https://doi.org/10.1016/j.agsy.2018.12.002

Biesmeijer JC (2006) Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. Science 313:351–354. https://doi.org/10.1126/science.1127863

Brookes G, Barfoot P (2017) Farm income and production impacts of using GM crop technology 1996–2015. GM Crops Food 8:156–193. https://doi.org/10.1080/21645698.2017.1317919

Burkle LA, Marlin JC, Knight TM (2013) Plant-pollinator interactions over 120 years: loss of species, co-occurrence, and function. Science 339:1611–1615. https://doi.org/10.1126/science.1232728

Cardoso P, Barton PS, Birkhofer K et al (2020) Scientists' warning to humanity on insect extinctions. Biol Conserv 242:108426. https://doi.org/10.1016/j.biocon.2020.108426

CCKP (2021) World Bank Climate Change Knowledge Portal. Climate data-projections. Morocco. https://climateknowledgeportal.worldbank.org/country/morocco/climate-data-projections. Accessed 22 Sep 2021

Chagnon M, Gingras J, DeOliveira D (1993) Complementary aspects of strawberry pollination by honey and IndigenQus bees (Hymenoptera). J Econ Entomol 86:416–420. https://doi.org/10.1093/jee/86.2.416

Chen K, Fijen TPM, Kleijn D, Scheper J (2021) Insect pollination and soil organic matter improve raspberry production independently of the effects of fertilizers. Agric Ecosyst Environ 309:107270. https://doi.org/10.1016/j.agee.2020.107270

Christmann S, Aw-Hassan A, Rajabov T et al (2017) Farming with alternative pollinators increases yields and incomes of cucumber and sour cherry. Agron Sustain Dev 37:24. https://doi.org/10.1007/s13593-017-0433-y

Christmann S, Aw-Hassan A, Güler Y et al (2021a) Two enabling factors for farmer-driven pollinator protection in low- and middle-income countries. Int J Agric Sustain 1–14. https://doi.org/10.1080/14735903.2021.1916254

Christmann S, Bencharki Y, Anougmar S et al (2021b) Farming with alternative pollinators benefits pollinators, natural enemies, and yields, and offers transformative change to agriculture. Sci Rep 11:18206. https://doi.org/10.1038/s41598-021-97695-5

Collier P, Conway G, Venables T (2008) Climate change and Africa. Oxf Rev Econ Policy 24:337–353

Connolly-Boutin L, Smit B (2016) Climate change, food security, and livelihoods in sub-Saharan Africa. Reg Environ Change 16:385–399. https://doi.org/10.1007/s10113-015-0761-x

de Lima KB, Ferreira PA, Groppo M et al (2020) Does landscape context affect pollination-related functional diversity and richness of understory flowers in forest fragments of Atlantic rainforest in Southeastern Brazil? Ecol Process 9:62. https://doi.org/10.1186/s13717-020-00261-6

Descamps C, Quinet M, Baijot A, Jacquemart A-L (2018) Temperature and water stress affect plant-pollinator interactions in *Borago officinalis* (Boraginaceae). Ecol Evol 8:3443–3456. https://doi.org/10.1002/ece3.3914

Dicks LV, Breeze TD, Ngo HT et al (2021) A global-scale expert assessment of drivers and risks associated with pollinator decline. Nat Ecol Evol 1–9. https://doi.org/10.1038/s41559-021-01534-9

Eilers EJ, Kremen C, Greenleaf SS et al (2011) Contribution of pollinator-mediated crops to nutrients in the human food supply. PLoS ONE 6:e21363. https://doi.org/10.1371/journal.pone.0021363

Elkouk A, El Morjani ZEA, Pokhrel Y et al (2021) Multi-model ensemble projections of soil moisture drought over North Africa and the Sahel region under 1.5, 2, and 3 °C global warming. Clim Change 167:1–18. https://doi.org/10.1007/s10584-021-03202-0

Ellis AM, Myers SS, Ricketts TH (2015) Do pollinators contribute to nutritional health? PLoS ONE 10:e114805. https://doi.org/10.1371/journal.pone.0114805

El Alaoui El Fels A, Saidi MEM, Bouiji A, Benrhanem M (2020) Rainfall regionalization and variability of extreme precipitation using artificial neural networks: a case study from western central Morocco. J Water Clim Change 12:1107–1122. https://doi.org/10.2166/wcc.2020.217

Feulner G (2017) Global challenges: climate change. Glob Challenges 1:5–6. https://doi.org/10.1002/gch2.1003

Filahi S, Tramblay Y, Mouhir L, Diaconescu EP (2017) Projected changes in temperature and precipitation indices in Morocco from high-resolution regional climate models. Int J Climatol 37:4846–4863. https://doi.org/10.1002/joc.5127

Filazzola A, Matter SF, MacIvor JS (2021) The direct and indirect effects of extreme climate events on insects. Sci Total Environ 769:145161. https://doi.org/10.1016/j.scitotenv.2021.145161

Free JB (1993) Insect pollination of crops. Academic

Garibaldi LA, Carvalheiro LG, Vaissière BE et al (2016) Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. Science 351:388–391. https://doi.org/10.1126/science.aac7287

Garratt MPD, Coston DJ, Truslove CL et al (2014) The identity of crop pollinators helps target conservation for improved ecosystem services. Biol Conserv 169:128–135. https://doi.org/10.1016/j.biocon.2013.11.001

Gérard M, Vanderplanck M, Wood T, Michez D (2020) Global warming and plant–pollinator mismatches. Emerg Top Life Sci 4:77–86. https://doi.org/10.1042/ETLS20190139
Ghanem H (2015) Agriculture and rural development for inclusive growth and food security in Morocco. In: Global economy & development working papers, no 82. Brookings Institution Press, Washington, DC
EL Gharous M, Boulal H (2016) IPNI North Africa challenges in nutrient management under rainfed agriculture of Morocco. Procedia Eng 138:332–336. https://doi.org/10.1016/j.proeng.2016.02.093
Giannini TC, Costa WF, Cordeiro GD et al (2017) Projected climate change threatens pollinators and crop production in Brazil. PLoS ONE 12:e0182274. https://doi.org/10.1371/journal.pone.0182274
Gingras D, Gingras J, De Oliveira D (1999) Visits of honeybees (Hymenoptera: Apidae) and their effects on cucumber yields in the field. J Econ Entomol 92:435–438. https://doi.org/10.1093/jee/92.2.435
Gomez-Zavaglia A, Mejuto JC, Simal-Gandara J (2020) Mitigation of emerging implications of climate change on food production systems. Food Res Int Ott Ont 134:109256. https://doi.org/10.1016/j.foodres.2020.109256
Goulson D (2019) The insect apocalypse, and why it matters. Curr Biol 29:R967–R971. https://doi.org/10.1016/j.cub.2019.06.069
Goulson D, Nicholls E, Botías C, Rotheray EL (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347:1255957. https://doi.org/10.1126/science.1255957
Grass I, Loos J, Baensch S et al (2019) Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. People Nat 1:262–272. https://doi.org/10.1002/pan3.21
Grass I, Batáry P, Tscharntke T (2021) Chapter six—Combining land-sparing and land-sharing in European landscapes. In: Bohan DA, Vanbergen AJ (eds) Advances in ecological research. Academic, pp 251–303
Hadri A, Saidi MEM, Saouabe T, El Alaoui El Fels A (2020) Temporal trends in extreme temperature and precipitation events in an arid area: case of Chichaoua Mejjate region (Morocco). J Water Clim Change 12:895–915. https://doi.org/10.2166/wcc.2020.234
Halsch CA, Shapiro AM, Fordyce JA et al (2021) Insects and recent climate change. Proc Natl Acad Sci 118. https://doi.org/10.1073/pnas.2002543117
Hanberry BB, DeBano SJ, Kaye TN et al (2020) Pollinators of the great plains: disturbances, stressors, management, and research needs. Rangel Ecol Manag. https://doi.org/10.1016/j.rama.2020.08.006
Hegland SJ, Nielsen A, Lázaro A et al (2009) How does climate warming affect plant-pollinator interactions? Ecol Lett 12:184–195. https://doi.org/10.1111/j.1461-0248.2008.01269.x
Henríquez-Piskulich PA, Schapheer C, Vereecken NJ, Villagra C (2021) Agroecological strategies to safeguard insect pollinators in biodiversity hotspots: Chile as a case study. Sustainability 13:6728. https://doi.org/10.3390/su13126728
Herrando S, Titeux N, Brotons L et al (2019) Contrasting impacts of precipitation on Mediterranean birds and butterflies. Sci Rep 9:5680. https://doi.org/10.1038/s41598-019-42171-4
Hill JK, Thomas CD, Huntley B (1999) Climate and habitat availability determine 20th century changes in a butterfly's range margin. Proc R Soc B Biol Sci 266:1197. https://doi.org/10.1098/rspb.1999.0763
Imbach P, Fung E, Hannah L et al (2017) Coupling of pollination services and coffee suitability under climate change. Proc Natl Acad Sci 114:10438–10442
IPBES (2016) The assessment report of the intergovernmental sciencepolicy platform on biodiversity and ecosystem services on pollinators, pollination and food production. In: Potts SG, Imperatriz-Fonseca VL, Ngo HT (eds) Secretariat of the Intergovernmental science-policy platform on biodiversity and ecosystem services. Bonn, Germany, p 552. https://doi.org/10.5281/zenodo.3402857

Karmaoui A, Zerouali S (2019) The need to establish a long-term ecological research network in Morocco as a tool to monitor ecosystems under climate change. In: Karmaoui A (ed) Climate change and its impact on ecosystem services and biodiversity in arid and semi-arid zones. IGI Global, pp 1–22. https://doi.org/10.4018/978-1-5225-7387-6.ch001

Kevan PG (1999) Pollinators as bioindicators of the state of the environment: species, activity and diversity. Agric Ecosyst Environ 74:373–393. https://doi.org/10.1016/S0167-8809(99)00044-4

Kevan P, Phillips T (2001) The economic impacts of pollinator declines: an approach to assessing the consequences. Conserv Ecol 5:8

Klanderud K, Birks HJB (2003) Recent increases in species richness and shifts in altitudinal distributions of Norwegian mountain plants. Holocene 13:1–6. https://doi.org/10.1191/0959683603hl589ft

Klein A-M, Vaissière BE, Cane JH et al (2007) Importance of pollinators in changing landscapes for world crops. Proc R Soc B Biol Sci 274:303–313. https://doi.org/10.1098/rspb.2006.3721

Kmoch L, Pagella T, Palm M, Sinclair F (2018) Using local agroecological knowledge in climate change adaptation: a study of tree-based options in Northern Morocco. Sustainability 10:3719. https://doi.org/10.3390/su10103719

Kremen C, Williams NM, Thorp RW (2002) Crop pollination from native bees at risk from agricultural intensification. Proc Natl Acad Sci 99:16812–16816. https://doi.org/10.1073/pnas.262413599

Kremen C, Iles A, Bacon C (2012) Diversified farming systems: an agroecological, systems-based alternative to modern industrial agriculture. Ecol Soc 17. https://doi.org/10.5751/ES-05103-170444

Kudo G, Ida TY (2013) Early onset of spring increases the phenological mismatch between plants and pollinators. Ecology 94:2311–2320. https://doi.org/10.1890/12-2003.1

Lhomme P, Michez D, Christmann S et al (2020) The wild bees (Hymenoptera: Apoidea) of Morocco. Zootaxa 4892:1–159. https://doi.org/10.11646/zootaxa.4892.1.1

Lumpkin T, Weinberger K, Moore S (2005) Increasing income through fruit and vegetable production opportunities and challenges

Marshman J, Blay-Palmer A, Landman K (2019) Anthropocene crisis: climate change, pollinators, and food security. Environments 6:22. https://doi.org/10.3390/environments6020022

McCracken ME, Woodcock BA, Lobley M et al (2015) Social and ecological drivers of success in agri-environment schemes: the roles of farmers and environmental context. J Appl Ecol 52:696–705. https://doi.org/10.1111/1365-2664.12412

McGregor SE (1976) Insect pollination of cultivated crop plants. Agricultural Research Service, U.S. Department of Agriculture

Memmott J, Waser NM, Price MV (2004) Tolerance of pollination networks to species extinctions. Proc R Soc B Biol Sci 271:2605–2611. https://doi.org/10.1098/rspb.2004.2909

Misra AK (2014) Climate change and challenges of water and food security. Int J Sustain Built Environ 3:153–165. https://doi.org/10.1016/j.ijsbe.2014.04.006

Mohammed B, Salah O, Driss O, Abdelghani C (2020) Global warming and groundwater from semi-arid areas: Essaouira region (Morocco) as an example. SN Appl Sci 2:1245. https://doi.org/10.1007/s42452-020-3014-7

Moinina A, Lahlali R, MacLean D, Boulif M (2018) Farmers' knowledge, perception and practices in apple pest management and climate change in the Fes-Meknes region, Morocco. Horticulturae 4:42. https://doi.org/10.3390/horticulturae4040042

Moore CE, Meacham-Hensold K, Lemonnier P et al (2021) The effect of increasing temperature on crop photosynthesis: from enzymes to ecosystems. J Exp Bot 72:2822–2844. https://doi.org/10.1093/jxb/erab090

Mugambiwa SS, Tirivangasi HM (2017) Climate change: a threat towards achieving 'sustainable development goal number two' (end hunger, achieve food security and improved nutrition and promote sustainable agriculture) in South Africa. Jàmbá J Disaster Risk Stud 9:350. https://doi.org/10.4102/jamba.v9i1.350

Murcia C (1990) Effect of floral morphology and temperature on pollen receipt and removal in *Ipomoea trichocarpa*. Ecology 71:1098–1109. https://doi.org/10.2307/1937378

Nicholson CC, Emery BF, Niles MT (2021) Global relationships between crop diversity and nutritional stability. Nat Commun 12:5310. https://doi.org/10.1038/s41467-021-25615-2

Ofori SA, Cobbina SJ, Obiri S (2021) Climate change, land, water, and food security: perspectives from Sub-Saharan Africa. Front Sustain Food Syst 5:218. https://doi.org/10.3389/fsufs.2021.680924

Ollerton J, Winfree R, Tarrant S (2011) How many flowering plants are pollinated by animals? Oikos 120:321–326. https://doi.org/10.1111/j.1600-0706.2010.18644.x

Ouraich I, Dudu H, Tyner WE, Cakmak EH (2019) Agriculture, trade, and climate change adaptation: a global CGE analysis for Morocco and Turkey. J North Afr Stud 24:961–991. https://doi.org/10.1080/13629387.2018.1463847

Ouraich I, Tyner WE (2015) Climate change impacts on Moroccan agriculture and the whole economy. https://doi.org/10.35188/UNU-WIDER/2014/804-9

Peñuelas J, Filella I, Comas P (2002) Changed plant and animal life cycles from 1952 to 2000 in the Mediterranean region. Glob Change Biol 8:531–544. https://doi.org/10.1046/j.1365-2486.2002.00489.x

Petersen JD, Reiners S, Nault BA (2013) Pollination services provided by bees in pumpkin fields supplemented with either *Apis mellifera* or *Bombus* impatiens or not supplemented. PLoS ONE 8:e69819. https://doi.org/10.1371/journal.pone.0069819

Picanço A, Gil A, Rigal F, Borges PAV (2017) Pollination services mapping and economic valuation from insect communities: a case study in the Azores (Terceira Island). Nat Conserv 18:1–25. https://doi.org/10.3897/natureconservation.18.11523

Potts SG, Biesmeijer JC, Kremen C et al (2010) Global pollinator declines: trends, impacts and drivers. Trends Ecol Evol 25:345–353. https://doi.org/10.1016/j.tree.2010.01.007

Potts SG, Imperatriz-Fonseca V, Ngo HT et al (2016) Safeguarding pollinators and their values to human well-being. Nature 540:220–229. https://doi.org/10.1038/nature20588

Powney GD, Carvell C, Edwards M et al (2019) Widespread losses of pollinating insects in Britain. Nat Commun 10:1018. https://doi.org/10.1038/s41467-019-08974-9

Radhouane L (2013) Climate change impacts on North African countries and on some Tunisian economic sectors. J Agric Environ Int Dev JAEID 107:101–113. https://doi.org/10.12895/jaeid.20131.123

Rafferty NE (2017) Effects of global change on insect pollinators: multiple drivers lead to novel communities. Curr Opin Insect Sci 23:22–27. https://doi.org/10.1016/j.cois.2017.06.009

Raza A, Razzaq A, Mehmood SS et al (2019) Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. Plants 8:34. https://doi.org/10.3390/plants8020034

Rochdane S, Bounoua L, Zhang P et al (2014) Combining satellite data and models to assess vulnerability to climate change and its impact on food security in Morocco. Sustainability 6:1729–1746. https://doi.org/10.3390/su6041729

Sabbahi R (2022) Economic value of insect pollination of major crops in Morocco. Int J Trop Insect Sci 42:1275–1284. https://doi.org/10.1007/s42690-021-00645-x

Sabbahi R, DeOliveira D, Marceau J (2005) Influence of honey bee (Hymenoptera: Apidae) density on the production of canola (Crucifera: Brassicacae). J Econ Entomol 98:367–372. https://doi.org/10.1093/jee/98.2.367

Sabbahi R, de Oliveira D, Marceau J (2006) Does the honeybee (Hymenoptera: Apidae) reduce the blooming period of canola? J Agron Crop Sci 192:233–237. https://doi.org/10.1111/j.1439-037X.2006.00206.x

Sabbahi R, Merzouki A, Guertin C (2009) Potential effect of *Beauveria bassiana* (Hypocreales: Clavicipitaceae) on *Anthonomus signatus* (Coleoptera: Curculionidae) in strawberries. Biocontrol Sci Technol 19:729–741. https://doi.org/10.1080/09583150903100815

Salzman S, Crook D, Calonje M et al (2021) Cycad-Weevil pollination symbiosis is characterized by rapidly evolving and highly specific plant-insect chemical communication. Front Plant Sci 12:816. https://doi.org/10.3389/fpls.2021.639368

Sánchez-Bayo F, Wyckhuys KAG (2019) Worldwide decline of the Entomofauna: a review of its drivers. Biol Conserv 232:8–27. https://doi.org/10.1016/j.biocon.2019.01.020
Saunders ME, Peisley RK, Rader R, Luck GW (2016) Pollinators, pests, and predators: recognizing ecological trade-offs in agroecosystems. Ambio 45:4–14. https://doi.org/10.1007/s13280-015-0696-y
Schilling J, Hertig E, Tramblay Y, Scheffran J (2020) Climate change vulnerability, water resources and social implications in North Africa. Reg Environ Change 20:1–12. https://doi.org/10.1007/s10113-020-01597-7
Settele J, Bishop J, Potts SG (2016) Climate change impacts on pollination. Nat Plants 2:1–3. https://doi.org/10.1038/nplants.2016.92
Sheldon AL (2012) Possible climate-induced shift of stoneflies in a southern Appalachian catchment. Freshw Sci 31:765–774. https://doi.org/10.1899/11-135.1
Simmons BI, Wauchope HS, Amano T et al (2020) Estimating the risk of species interaction loss in mutualistic communities. PLOS Biol 18:e3000843. https://doi.org/10.1371/journal.pbio.3000843
Soroye P, Newbold T, Kerr J (2020) Climate change contributes to widespread declines among bumble bees across continents. Science 367:685–688. https://doi.org/10.1126/science.aax8591
Stein K, Coulibaly D, Stenchly K et al (2017) Bee pollination increases yield quantity and quality of cash crops in Burkina Faso, West Africa. Sci Rep 7:17691. https://doi.org/10.1038/s41598-017-17970-2
Stewart JE, Illán JG, Richards SA et al (2020) Linking inter-annual variation in environment, phenology, and abundance for a montane butterfly community. Ecology 101:e02906. https://doi.org/10.1002/ecy.2906
Tibesigwa B, Siikamäki J, Lokina R, Alvsilver J (2019) Naturally available wild pollination services have economic value for nature dependent smallholder crop farms in Tanzania. Sci Rep 9:3434. https://doi.org/10.1038/s41598-019-39745-7
UNESCO (2004) The water resources in the OSS (Observatory of the Sahara and the Sahel) countries; evaluation, use and management; International Hydrological Programme. Published in 2004; 7, place de Fontenoy, 75352, Paris 07 SP
van der Sluijs JP, Vaage NS (2016) Pollinators and global food security: the need for holistic global stewardship. Food Ethics 1:75–91. https://doi.org/10.1007/s41055-016-0003-z
van Engelsdorp D, Hayes J Jr, Underwood RM, Pettis J (2008) A survey of honey bee colony losses in the U.S., fall 2007 to spring 2008. PLoS ONE 3:e4071. https://doi.org/10.1371/journal.pone.0004071
Vanbergen AJ and the Insect Pollinators Initiative (2013) Threats to an ecosystem service: pressures on pollinators. Front Ecol Environ 11:251–259. https://doi.org/10.1890/120126
Vasiliev D, Greenwood S (2021) The role of climate change in pollinator decline across the Northern Hemisphere is underestimated. Sci Total Environ 775:145788. https://doi.org/10.1016/j.scitotenv.2021.145788
Walther G-R (2003) Plants in a warmer world. Perspect Plant Ecol Evol Syst 6:169–185. https://doi.org/10.1078/1433-8319-00076
Warren MS, Maes D, Swaay CAM van et al (2021) The decline of butterflies in Europe: problems, significance, and possible solutions. Proc Natl Acad Sci 118. https://doi.org/10.1073/pnas.2002551117
Williams IH (1994) The dependence of crop production within the European Union on pollination by honey bees. Agric Sci Rev 6:229–257
Wurz A, Grass I, Tscharntke T (2021) Hand pollination of global crops—a systematic review. Basic Appl Ecol 56:299–321. https://doi.org/10.1016/j.baae.2021.08.008
Zhang Y, Niu H, Yu Q (2021) Impacts of climate change and increasing carbon dioxide levels on yield changes of major crops in suitable planting areas in China by the 2050s. Ecol Indic 125:107588. https://doi.org/10.1016/j.ecolind.2021.107588

Dr. Rachid Sabbahi is a Professor at the Higher School of Technology—Laayoune, Ibn Zohr University, Morocco, since 2019. He completed a B.Sc. in Animal Biology at Hassan II University of Casablanca, Morocco, a M.Sc. (2003) and a Ph.D. (2008) in Biological Sciences at Quebec University, Montreal, Canada. Dr. Sabbahi is specialized in biological control of insect pests and plant diseases, plant-microbe interaction, environmental microbial biotechnology, and insect pollination and crop production. In addition, he has co-managed many research projects both nationally and internationally, published several scientific papers and participated in many international conferences.

Impacts of Climate Change on Food Security and Health: Medicinal and Aromatic Plants (MAPs) in the Pamir Region of Tajik and Afghan Badakhshan

Ali Aziz, Munira Karamkhudoeva, and Michael Keusgen

Abstract Situated at the junction of Asia's largest mountain ranges—the Himalayas, Karakoram, Hindu Kush, and Tien Shan—the valleys of the Pamir Mountains share a rich and common flora, fauna, and geography. The residents of the Pamirs, given their remote location and high poverty rates, traditionally relied on local plants for food and treatment of illnesses. This makes evident the strong relation and dependency of Pamir communities on medicinal plants for both food security/livelihoods and health purposes. As traditional medicine continues to provide health care for remote mountain communities in the Pamirs, the rapidly changing climatic conditions impacting medicinal plant populations in their natural habitats make mountain communities more vulnerable to different ailments and food insecurity. Evidence shows that climate change is triggering visible effects on plant populations as well as their distribution in certain geographies. This study documents the impacts of climate change on medicinal and aromatic plants (MAPs) and food security, lists available MAPs, their uses as medicine and food, and discusses conservation-related issues in the research area. Over a five-year period, local respondents revealed that MAP populations are declining rapidly and shifting from lower to higher elevations. This empirical work confirms that while MAP resources were abundant in the region 15–20 years ago, these resources are rapidly depleting due to anthropogenic and climatic factors. The indigenous knowledge of medicinal plants is rapidly declining as well. Local healers producing herbal remedies tend to share their knowledge through oral communication with family members who, in turn, are less likely to transcribe these remedies or pursue indigenous systems of treating human ailments. These findings on the potential importance of MAPs should be shared with indigenous communities including the effects of their disappearance on both the traditional health and

A. Aziz (✉)
Mountain Societies Research Institute (MSRI), University of Central Asia (UCA), Khorog, Tajikistan
e-mail: azizali.khan@ucentralasia.org

M. Karamkhudoeva
Pamir Biological Institute (PBI) Khorog GBAO, Khorog, Tajikistan

M. Keusgen
Philipps University, Marburg, Germany
e-mail: keusgen@staff.uni-marburg.de

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_9

food systems of mountain communities. Such knowledge and technology transfer will help protect medicinal plants from extinction as well as preserve and sustain the practice of herbal medicine. Finally, recording indigenous knowledge, concerning the use and preparation of medicinal plants, ensures the preservation of this endemic culture.

Keywords Badakhshan · Climate change · Food security · Livelihoods · MAPs · Pamir Mountains

1 Introduction

Studies on medicinal and aromatic plants (MAPs) have focused on the availability, usage for local herbal remedies, food and culinary purposes, and the chemical constituents of different MAPs, particularly in Tajik Badakhshan. These studies highlighted the importance of MAP resources for the traditional health care, food security, and the preservation of traditions/cultures and rituals associated with MAPs in the Pamirs. However, the emerging and important aspects of climate change and its effects and impact on indigenous MAPs, rural livelihoods, and food security have not yet received significant scientific inquiry.

The mountain regions have their own peculiarities and characteristics. People in these areas are especially vulnerable to food insecurity due to low productivity, subsistence economies, constraints of terrain and climate, poor infrastructure, limited access to markets, physical isolation, vulnerability to natural risks, and high cost of food production and transport (Rasul and Hussain 2015).

A crucial gap exists in current ethno-pharmacological and medicinal plant research, which impacts a wide-range of factors affecting sustainable, socioculturally equitable, and safe supplies of herbal medicines (Booker et al. 2012). Research on the potential for MAP development in Badakhshan is especially fragmented and scarce. However, certain trends suggest ways forward using MAPs to increase incomes by linking to regional and international markets and promote sustainable practices (ICARDA 2006; Jeppesen et al. 2012; Kassam et al. 2010; Kruse 2015; Soelberg 2016).

There are reports documenting useful plants in Wakhan (Soelberg 2016) as well as valuable information about wildlife, and socioeconomic frameworks in Darwaz exist (Moheb and Mostafawi 2012). However, there is a severe imbalance of information about MAPs in other districts of Badakhshan, as there are very few direct references to plants found in these districts.

The literature on MAPs and livelihood improvement suggests that MAPs "have a huge potential for remote communities that practice subsistence agriculture and have limited access to the regional economy" (Sher et al. 2014: 2). Badakhshan, geographically located at the junctions of Asia's mightiest mountain ranges, harbors

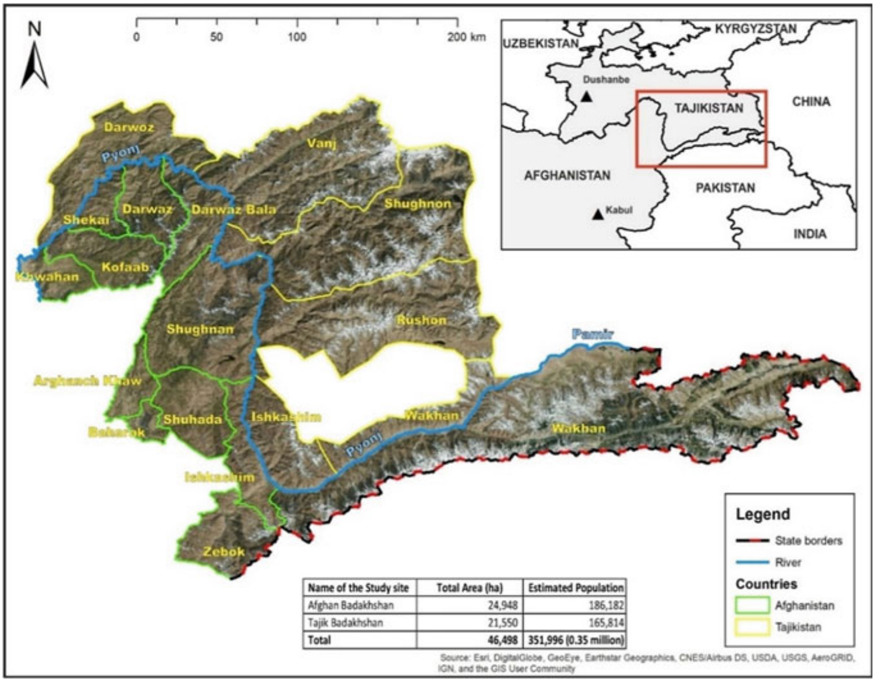


Fig. 1 Study area of mountain communities in the Pamir Region of Tajik and Afghan Badakhshan

diverse flora and fauna. The affinities to different mountain ranges and high vertical relief offer a variety of habitats, thus supporting a rich and unique biodiversity (Aziz 2021) (Fig. 1).

The indigenous peoples of the Pamir Mountains hold a vast knowledge about their environment. For centuries, they have been living in proximity with nature to sustain their livelihoods. Traditionally, they were engaged in the conservation of species important for food security and health systems. This included domesticating species, storing seeds/propagules, budding, grafting, and exchanging seeds within and outside the villages, and conserving species in the mountains, forests, and pastures (Aziz 2021).

However, climate change has a considerable effect on food security. The food insecurity levels in Gorno-Badakhshan Autonomous Oblast (GBAO) province consistently exceeded 20% of the population for the period for which the data was available (WFP 2017). Thus, this study on the importance of MAPs to indigenous communities within the context of climate change aims at investigating how mountain communities use and depend on MAPs for sustenance and health care in the study areas; and exploring and documenting the impacts of climate change on MAPs and, therefore, the food security of mountain communities in the Pamirs.

2 Materials and Methods

To achieve the above-mentioned objectives, the following research methods were developed.

2.1 Research Design

For the field research and investigation, a multistage random sampling technique was adopted for the selection of research sites. In the first stage, the research districts were selected randomly in both Tajik and Afghan Badakhshan. In the second stage, the villages/valleys were selected randomly in both Tajik and Afghan Badakhshan. In the last stage, the households were selected again randomly. The information on villages, population, and household details was collected from provincial statistic departments/offices in both GBAO of Tajikistan and Afghan Badakhshan to determine the pool of villages from which the random sample will be selected. The sample size was kept at 20% in all stages of sampling and surveys because of the vast geographies of the study area.

2.2 Data Collection

A structured questionnaire was constructed for data collection in the field. Between 2016 and 2020, a total of 200 interviews were conducted in five border districts of Afghan Badakhshan, including Zebak, Ishkashim, Wakhan, Shughnan, and Nusai-Darwaz, as well as four districts in Tajik Badakhshan, including Shughnan, Roshan, Ishkashim, and Wakhan. After obtaining the verbal informed consent from each participant, the interviews of men (44%) and women (56%) were conducted in their own homes, offices, shops, agriculture fields and pastures. The level of education in Afghan Badakhshan was very low, particularly among women respondents (i.e., 5% women had completed primary level or had informal education and hardly 10% of men had primary and secondary education). On the other hand, in Tajik Badakhshan, nearly 100% men and women respondents were literate, mostly at bachelor's level.

2.3 Focus Group Discussion

In addition to interviews, focus group discussions were held with relevant professionals and key knowledge holders in Ishkashim and Nusai-Darwaz districts of Afghan Badakhshan and Khorog town of Tajik Badakhshan. The structured questionnaire was used to assess and collect information on MAP availability, usage, current distribution status, population trends, and the impact of emerging climate change. The group members were identified through detailed consultations with senior colleagues from Aga Khan Foundation (AKF) Area Offices of Ishkashim (Afghan Badakhshan) and AKF Khorog Area Office (Tajikistan). This enabled us to engage the most knowledgeable people associated with medicinal plant collection, local herbal healers/hakims, and local traders of medicinal plants. The information generated in the focus group was further discussed in individual meetings as a conscious effort to obtain an accurate record.

3 Results

Field interviews revealed that the Pamir Mountain communities largely depend on the natural environment. These 200 respondents described their habitat as necessary to meet their daily livelihood needs, particularly for herbal remedies and food. Data illustrated residents in the study area to use 128 different plant species belonging to 63 families and 81 genera for health-related and nourishment purposes. Another similar study in Afghan Badakhshan records 310 distinct uses of 58 medicinal plants species in 63 categories of treatment and preventions (Kassam et al. 2010).

3.1 Contribution of MAPs to Local Culinary and Food

Food insecurity and malnutrition are serious and prevalent in the Pamirs. In 2012, only 0.1% of people in Afghan Badakhshan were food secure (Kruse 2015). The local population in Badakhshan equates "food" with "medicine"; therefore, protecting MAPs is directly linked with food security and sovereignty (Soelberg 2016; Kassam et al. 2010, 2013; Adhikari et al. 2017). The research in this region revealed that 62% of medicinal plants, which contribute to health security and sovereignty, are also used for food purposes. The distinctions between plants as food and medicine are seen to be problematic, as many plant uses are known to provide both nutritive and other medicinal benefits simultaneously (Kassam et al. 2010).

Our study in the Tajik and Afghan Badakhshan illustrated that 68 medicinal plant species are simultaneously used to treat human ailments locally as well as for food and beverages. This includes herbal tea, juices, compotes (fruits preserved in syrup), jams, salads, soups, dry fruits, nuts, and spices, therefore making evident the strong relation and dependency of Pamir communities on medicinal plants for both food security and herbal remedies (Table 1). A similar study in Pamir region supports these findings as 62% of medicinal plants used in the Pamirs are also used for food (Kassam et al. 2010).

Table 1 shows that 68 medicinal plant species belonging to 20 plant families are also used for family food and nutrition purposes. However, due to anthropogenic pressure coupled with climate change, 22 plants (32%) are decreasing a lot from

Table 1 MAPs used for local food and dishes in both Tajik and Afghan Badakhshans

Local uses of plants	# of plants used	Tajiki/Pamiri and Dari name of plants	English names	Scientific names	Plant family	Current status
Herbal teas	12	*Jambilak*	Blue mint	*Ziziphora pamiroalaica* Juz ex Nevski.	Lamiaceae	Decreasing a lot
		Rishtakashak	plantain	*Plantago lanceolata* L.	Plantaginaceae	Decreasing a lot
		Podina	Mint	*Mentha asiatica* Boriss.	Lamiaceae	Stable
		Gulkhor	Dog rose	*Rosa canina* L.	Rosaceae	Stable
		Shirinboya, muthq	Licorice root	*Glycyrrhiza glabra* L.	Fabaceae	Decreasing a lot
		Ramashka	Chamomile	*Matricaria chamomilla* L.	Asteraceae	Decreasing a lot
		Kachalo e khamkhurak	Sunchoke	*Helianthus tuberosus* L.	Asteraceae	Stable
		Qaraqat, Qot e siah	Black currant	*Ribes nigrum* L.	Grossulariaceae	Decreasing a lot
		Zargul	Barberry	*Berberis vulgaris* L.	Berberidaceae	Decreasing a lot
		Zeera	Black cumin	*Bunium persicum* Boiss.	Apiaceae	Decreasing a lot
		Shibit	Dill	*Anethum graveolens* L.	Apiaceae	Decreasing a lot
		Marmarak	Clary sage	*Salvia sclarea* var. *turkestaniana* Mottet.	Lamiaceae	Decreasing a lot
Vegetables/curries	10	*Gashniz*	Coriander	*Coriandrum sativum* L.	Apiaceae	Stable
		Chosnuk/Seer	Garlic	*Allium sativum* L.	Amaryllidaceae	Stable
		Musfar	Safflower	*Carthamus tinctorius* L.	Asteraceae	Decreasing a lot
		Kadu	Pumpkin	*Cucurbita pepo* L.	Cucurbitaceae	Stable
		Lablabu	Beetroot	*Beta vulgaris* L.	Amaranthaceae	Stable
		Boqlajan/ Bodinjan e Siah	Eggplant	*Solanum melongena* L.	Solanaceae	Stable

(continued)

Table 1 (continued)

Local uses of plants	# of plants used	Tajiki/Pamiri and Dari name of plants	English names	Scientific names	Plant family	Current status
		Grechka	Buckwheat	*Fagopyrum esculentum* Moench	Polygonaceae	Decreasing a lot
		Zardak	Carrot	*Daucus carota* L.	Apiaceae	Stable
		Zaghir	Flax/lint	*Linum usitatissimum* L.	Linaceae	Deceasing a lot
		Karam	Cabbage	*Brassica oleracea* L.	Brassicaceae	Stable
Dry fruits/nuts	9	*Zardalu*	Apricot	*Prunus armeniaca* L.	Rosaceae	Stable
		Sinjid, Seezd	Russian olive	*Elaeagnus angustifolia* L.	Elaeagnaceae	Decreasing a little
		Chormagz	Walnut	*Juglans regia* L.	Juglandaceae	Decreasing a lot
		Tut	Mulberry	*Morus alba* L.	Moraceae	Decreasing a little
		Seb	Apple	*Prunus malus* L.	Rosaceae	Stable
		Alabolu	Wild cherry	*Prunus avium* L.	Rosaceae	Decreasing a little
		Gilas	Sweet cherry	*Cerasus avium* L.	Prunaceae	Decreasing a little
		Injeer	Fig	*Ficus carica* L.	Moraceae	Decreasing a little
		Badam	Almond	*Prunus amygdalus* Batsch.	Prunaceae	Decreasing a lot
Jams/pickles	10	*Angat*	Seabuckthorn	*Hippophae rhamnoides* L.	Elaeagnaceae	Decreasing a little
		Malina	Raspberry	*Rubus crataegifolius* Bunge.	Rosaceae	Decreasing a lot
		Seb	Apple	*Prunus malus* L.	Rosaceae	Stable
		Zardalo	Apricot	*Prunus armeniaca* L.	Rosaceae	Stable

(continued)

Table 1 (continued)

Local uses of plants	# of plants used	Tajiki/Pamiri and Dari name of plants	English names	Scientific names	Plant family	Current status
		Shaftalo	Peach	*Prunus persica* L.	Rosaceae	Stable
		Kamol/Rav	Stinking gum	*Ferula assafoetida* L.	Apiaceae	Decreasing a lot
		Gilas	Sweet cherry	*Cerasus avium* L.	Rosaceae	Decreasing a little
		Koksulton Aloocha	Plum	*Prunus domestica* L.	Rosaceae	Decreasing a little
		Nok	Pear	*Pyrus persica* Pers.	Rosaceae	Decreasing a little
		Chokri	Rhubarb	*Rheum emodi* Wall ex Meisn.	Polygonaceae	Decreasing a little
Juices/compotes	12	*Anar*	Pomegranate	*Punica granatum* L.	Anacardiaceae	Decreasing a lot
		Gilas	Sweet cherry	*Cerasus avium* L.	Rosaceae	Decreasing a little
		Dolana	Hawthorn	*Crataegus sanguinea* Pall.	Rosaceae	Decreasing a little
		Malina	Raspberry	*Rubus crataegifolius* Bunge.	Rosaceae	Decreasing a lot
		Seb	Apple	*Pyrus malus* L.	Rosaceae	Stable
		Qaraqat	Black currant	*Ribes nigrum* L.	Grossulariaceae	Decreasing a lot
		Kamal, Rav, Hing	Stinking gum	*Ferula assafoetida* L.	Apiaceae	Decreasing a lot
		Angat	Seabuckthorn	*Hippophae rhamnoides* L.	Elaeagnaceae	Decreasing a little
		Zardalu	Apricot	*Prunus armeniaca* L.	Rosaceae	Stable
		Tut, Uslai Tut	Mulberry	*Morus alba* L.	Moraceae	Decreasing a little
		Shahtut	Black mulberry	*Morus nigrum* L.	Moraceae	Decreasing a little
		Koksulton/ Aloocha	Plum	*Prunus domestica* L.	Rosaceae	Decreasing a little

(continued)

Table 1 (continued)

Local uses of plants	# of plants used	Tajiki/Pamiri and Dari name of plants	English names	Scientific names	Plant family	Current status
Salads/spices	9	*Gashniz*	Coriander	*Coriandrum sativum* L.	Apiaceae	Stable
		Zeera	Black cumin	*Bunium persicum* Boiss.	Apiaceae	Decreasing a lot
		Budering	Cucumber	*Cucumis sativus* L.	Cucurbitaceae	Stable
		Anzur Piyoz	Wild onion	*Allium stipitatum* Regel.	Amaryllidaceae	Decreasing a lot
		Badiyan	Fennel	*Foeniculum vulgare* Mill.	Apiaceae	Stable
		Chosnuk/Seer	Garlic	*Allium sativum* L.	Amaryllidaceae	Stable
		Lablabu	Red beet	*Beta vulgaris* L.	Amaranthaceae	Stable
		Rawash	Rhubarb	*Rheum maximowiczii* Losinsk.	Polygonaceae	Stable
		Podina, Wuthn	Mint	*Mentha asiatica* Boriss.	Lamiaceae	Stable
Soups	6	*Zardghul*	Barberry	*Berberis vulgaris* L.	Berberidaceae	Decreasing a little
		Kavar	Caper	*Capparis spinosa* Wild.	Capparidaceae	Decreasing a little
		Boqla	Horse bean	*Vicia faba* L.	Fabaceae	Decreasing a little
		Zardak	Carrot	*Daucus carota* L.	Apiaceae	Stable
		Chichivitsa/dal	Brown Lentil	*Lens culinaris* Medikus.	Fabaceae	Decreasing a little
		Lobia surkh	Red bean	*Phaseolus vulgaris* L.	Fabaceae	Stable
Total MAPs used in different foods	68					

Note Some species of MAPs are multi-purpose and therefore repeatedly appear for different food categories their natural environment/habitat; 20 plants species (30%) are decreasing a little; and 26 plant species (38%) are reported stable in the study areas. It means 42 (62%) of the available medicinal plants having additional food and nutritional value for the poor mountain families are depleting from their natural habitat in the study areas, which may negatively impact the local food security system in the long run.

3.2 Contribution of MAPs to Traditional Health System

The Pamir region is home to an impoverished multi-ethnic population closely connected to the land. Amidst extreme climatic and geographic conditions, the high-quality medicinal and aromatic plant species have thrived and adapted. In response, the local population possesses valuable indigenous knowledge on the medicinal use of local plants to promote health. Our study revealed that over 30 different human ailments/diseases are treated traditionally by 128 different medicinal plant species, including 68 mentioned in Table 1. These species are found locally by resident hakims/tabibs and herbalists both in Tajik and Afghan Badakhshan. The eight most common human ailments treated by MAPs are shown in Table 2.

Table 2 shows that 48 medicinal plant species belonging to 17 plant families are used for the common human ailments and diseases in the study areas. However, due to anthropogenic pressure coupled with climate change 17 medicinal plants (36%) are decreasing a lot from their natural environment/habitat. Sixteen medicinal plants species (33%) are decreasing a little and 15 medicinal plant species (31%) are reported stable in the study areas. It means that 33 (69%) of the available medicinal plants are depleting from their natural habitat in the study areas, which may deprive the local mountain communities of the traditional health benefits from the medicinal plant resource as a cheap and natural remedy in the long run.

Furthermore, a similar study in Pamir region noted that the "*conversations with villagers and nomadic pastoralists throughout the Pamirs reveal that medicinal plants enable these communities to determine their own healthcare systems, especially under conditions of dramatic ecological and social change*" (Kassam et al. 2013). The most recent publication on the subject in this region reveals that medicinal plants are consumed on a regular basis, and are often described as both food and medicine, and likely provide important nutrients otherwise lacking in people's diets. In remote mountain communities, where agriculture relies on favorable weather, and crop failures can be devastating, especially if roads are blocked by foods, avalanches, mudflows, or rockfalls, the availability of non-cultivated plants serving as food and medicine can prevent starvation (Karamkhudoeva et al. 2021).

MAPs are important for the overall health of people in the Pamir Mountains, particularly in isolated valleys that have limited access to medical facilities. MAPs not only provide inexpensive and safe herbal remedies, but they are also associated with many traditional rituals.

Table 2 List of 8 common human diseases and traditional herbal remedies

Common human ailments/diseases	Local name of the MAPs	English name of MAPs	Latin names of MAPs	Plant family	Current status
1. Cardiovascular diseases	*Ramashka/Gul e Babuna*	Chamomile (flowers)	*Matricaria chamomilla* L.	Asteraceae	Decreasing a lot
	Qaraqat/Qot e Siah	Black currant (fruits)	*Ribes nigrum* L.	Grossulariaceae	Decreasing a lot
	Angat	Seabuckthorn (fruits)	*Hippophae rhamnoides* L.	Elaeagnaceae	Decreasing a little
	Kachalo e khamkhurak	Sunchoke (tubers)	*Helianthus tuberosus* L.	Asteraceae	Stable
	Chosnuk/Seer	Garlic (bulbs)	*Allium sativum* L.	Amaryllidaceae	Stable
	Lablabu	Beetroot (tubers)	*Beta vulgaris* L.	Amaranthaceae	Stable
	Zhovd/Noshnedz	Apricot (gum)	*Prunus armeniaca* L.	Rosaceae	Stable
2. High blood pressure	*Jambilak*	Blue Mint (Leaves/flowers)	*Ziziphora pamiroalaica* Juz. ex Nevski	Lamiaceae	Decreasing a lot
	Zargul/Zarghul	Barberry (fruits)	*Berberis vulgaris* L.	Berberidaceae	Decreasing a little
	Shibit	Dill (seeds)	*Anethum graveolens* L.	Apiaceae	Decreasing a lot
	Podina	Mint (leaves)	*Mentha arvensis* L.	Lamiaceae	Stable
	Rawash/Chukri	Rhubarb (stems)	*Rheum emodi* Wall. ex Meisn	Polygonaceae	Decreasing a little
	Kachalo e khamkhurak	Sunchoke (tubers)	*Helianthus tuberosus* L.	Asteraceae	Stable
	Seer/Chosnuk	Garlic (bulb/leaves)	*Allium sativum* L.	Amaryllidaceae	Stable
	Gilas	Cherry (fruits)	*Prunus avium* L.	Rosaceae	Decreasing a little

(continued)

Table 2 (continued)

Common human ailments/diseases	Local name of the MAPs	English name of MAPs	Latin names of MAPs	Plant family	Current status
3. Gastrointestinal problems	*Podina*	Mint (Leaves)	*Mentha asiatica* Boriss.	Lamiaceae	Stable
	Zeera	Black cumin (seeds)	*Bunium persicum* Boiss.	*Apiaceae*	*Decreasing a lot*
	Gashniz	Coriander (leaves/seeds)	*Coriandrum sativum* L.	Apiaceae	Stable
	Tut	Mulberry (fruits)	*Morus alba* L.	Moraceae	Decreasing a little
	Injeer	Fig (fruits)	*Ficus carica* L.	Moraceae	Decreasing a little
	Angat	Seabuckthorn (fruits)	*Hippophae rhamnoides* L.	Elaeagnaceae	Decreasing a little
	Anar	Pomegranate (fruits)	*Punica granatum* L.	Anacardiaceae	Decreasing a lot
	Pudina	Mint (leaves)	*Mentha arvensis* L.	Lamiaceae	Stable
4. Cough/Bronchitis	*Masfar*	Safflower (flowers)	*Carthamus tinctorius* L.	Asteraceae	Decreasing a lot
	Ramashka/Gul e Babuna	Chamomile (flowers)	*Matricaria chamomilla* L.	Asteraceae	Decreasing a lot
	Chormaghz	Walnut (nuts)	*Juglans regia* L.	Juglandaceae	Decreasing a lot
	Alabalu	Wild Cherry (fruits)	*Prunus avium* L.	Rosaceae	Decreasing a little
	Injeer	Fig (fruits)	*Ficus carica* L.	Moraceae	Decreasing a little
	Anar	Pomegranate (fruits)	*Punica granatum* L.	Anacardiaceae	Decreasing a lot

(continued)

Table 2 (continued)

Common human ailments/diseases	Local name of the MAPs	English name of MAPs	Latin names of MAPs	Plant family	Current status
5. Urinary tract infection (UTI), kidney stones and pain	*Rishtakashak/Ragakwokh/Barg e zuf*	Ribwort plantain (seeds)	*Plantago lanceolata* L.	Plantaginaceae	Decreasing a lot
	Gulkhar	Dogrose (fruits)	*Rosa canina* L.	Rosaceae	Stable
	Pupaki juvorimaka	Corn silk (flowers)	*Maydis stigmata* L.	Poaceae	Stable
	Tut	Mulberry (fruits)	*Morus alba* L.	Moraceae	Decreasing a little
	Badam	Almond (nuts)	*Prunus amygdalus* Batsch.	Prunaceae	Decreasing a lot
	Ragakvokh/bargi zuf	Broadleaf plantain (seeds)	*Plantago major* L.	Plantaginaceae	Decreasing a lot
	Zardak	Carrot (roots)	*Daucus carota* L.	Apiaceae	Stable
	Hing/ Kamol/Rav	Stinking gum (gum)	*Ferula assafoetida* L.	Apiaceae	Decreasing a lot
	Zhovd (Sinjid, Seezd)	Russian olive (fruits)	*Elaeagnus angustifolia* L.	Elaeagnaceae	Decreasing a little
6. Arthritis, Joint pain, inflammation	*Karam*	Cabbage (leaves)	*Brassica oleracea* L.	Brassicaceae	Stable
	Ramashka/Gul e Babuna	Chamomile (flowers)	*Matricaria chamomilla* L.	Asteraceae	Decreasing a lot
	Anar	Pomegranate (fruit shell)	*Punica granatum* L.	Anacardiaceae	Decreasing a lot
	Zargul/Zarghul	Barberry (roots)	*Berberis vulgaris* L.	Berberidaceae	Decreasing a little

(continued)

Table 2 (continued)

Common human ailments/diseases	Local name of the MAPs	English name of MAPs	Latin names of MAPs	Plant family	Current status
7. Jaundice, Liver disease	*Pupaki juvorimaka*	Corn silk (flowers)	*Maydis stigmata* L.	Poaceae	Stable
	Angat	Seabuckthorn (fruits)	*Hippophae rhamnoides* L.	Elaeagnaceae	Decreasing a little
	Kamol/Rav	Stinking gum (gum)	*Ferula assafoetida* L.	Apiaceae	Decreasing a lot
8. Gynecological diseases/problems	*Ramashka/Gul e Babuna*	Chamomile (flowers)	*Matricaria chamomilla* L.	Asteraceae	Decreasing a lot
	Angat	Seabuckthorn (fruits)	*Hippophae rhamnoides* L.	Elaeagnaceae	Decreasing a little
	Zhovd (Sinjid, Seezd)	Russian olive (gum)	*Elaeagnus angustifolia* L.	Elaeagnaceae	Decreasing a little

Note Some species of MAPs are multi-purpose and therefore repeatedly appear for different ailment/disease categories

3.3 Contribution of MAPs to Livelihoods

Medicinal plants account for around 20% of exports of Afghanistan and have great potential for further contribution to national income of the country. Afghanistan is an important exporter of medicinal plant; each year more than 45 different species are being exporting to different countries. Reports show that during 2015, about 20 different medicinal plants (38,070.401 tons) with total value of USD 130,179,374 have been exported. According to the Afghanistan NRM Strategy (2017–2021), Liquorice (*Glycyrrhiza glabra*) and stinking gum (*Ferula assafoetida*) were the major export items of the country and are mainly exporting roots and extracts, but not with consideration of value chain and processing inside the country. The strategy acknowledges that commercialization could lead to overexploitation of medicinal plants and ultimately jeopardize local people's livelihoods. Therefore, the strategy advocates for community-based management that builds on indigenous ecological knowledge to develop policies that can support sustainable use, conservation, and restoration. Such policies will need to be mindful of climate change. For example, the government aims to increase the hectarage of medicinal plants (including licorice and asafetida) by 2500 ha. However, in selecting restoration sites, agencies need to consider current as well as projected climate conditions and whether they can support self-propagating populations over the long term (Karamkhudoeva et al. 2021).

The livelihoods of many poor mountain dwellers depend heavily on the collection and selling of various medicinal plants both at local and national markets in Tajik and Afghan Badakhshan. This study revealed that 89 medicinal plant species are traded in local markets, including licorice roots (*Glycyrrhiza glabra* L.), black currant (*Ribes nigrum* L.), golden root (*Rhodiola rosea* L.), stinking gum (*Ferula assafoetida* L.), black cumin (*Bunium persicum* Boiss.), St. John's wort (*Hypericum perforatum* L.), mint (*Mentha longifolia var. asiatica* L.), rosehips (*Rosa canina* L.), buckwheat (*Fagopyrum esculentum* Moench.), chamomile (*Matricaria chamomilla* L.), barberry (*Berberis vulgaris* L.), Russian olive (*Elaeagnus angustifolia* L.), and caper (*Capparis spinosa* L.). Most species are used for food as well as medicines. In particular, the flowers, fruits, and roots were among the most valuable parts of the plants.

3.4 Impact of Climate Change on MAPs in Pamir Region

The reality of climate change and its impacts are more visible in mountainous regions like the Pamirs of Afghan and Tajik Badakhshan (personal observation and focus group discussion). Observed by local communities, the changing weather trajectory is slowly affecting the local ecology and environmental conditions. Most respondents confirm that the availability of natural resources—including water, forests, wildlife, and medicinal plant species—is slowly decreasing (Figs. 2 and 3).

Fig. 2 Snowfall in the month of October. *Source* Photos anonymous

Fig. 3 Snowfall in May *Source* Photos anonymous

The interviews and focus group discussions revealed that MAPs were regularly found around villages. However, this was common 10–15 years ago, and the 50–60 species are now becoming rare. Respondents described MAPs sporadic appearance in lower and higher mountains due to the reasons described in Table 3 and Fig. 4.

Table 3 Respondents' perception on MAPs

Reasons for depletion of MAPs given by respondents	% Respondents
Anthropogenic pressure (human and livestock)	47
Inappropriate collection (wrong time and methods)	33
Effects and impact of climate change	20

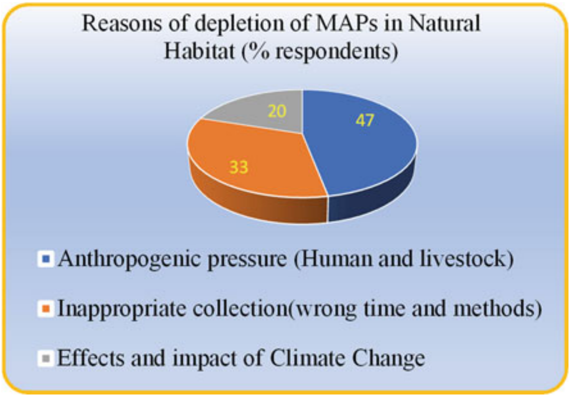


Fig. 4 Respondents' perception on MAPs

3.5 Reasons Behind MAPs the Depletion in Natural Habitats

Around 47% of respondents attributed the changes in medicinal plant populations to anthropogenic or biotic pressure caused by both human and livestock grazing. The increasing awareness among communities about the safety and low cost of herbal remedies and the use of natural organic medicines have caused MAP collection to increase over the years. Moreover, high demand exists both at local and national markets for different MAPs and their products (market survey by the author for another study). During the field investigation and surveys, MAPs were observed to be collected for household consumption of food and herbal remedies as well as sold by many villagers, including women and children, to earn livelihoods. This was particularly common along the Panj River, on both sides, in addition to local and cross-border markets at Tem Khorog, Ishkashim, and Ruzvoy/Nusai. The high market demand exerts a continuous pressure on MAPs, which causes a decline in populations.

Other studies, such as Karamkhudoeva (2017) and Kassam et al. (2010), support that the population of MAPs species are decreasing due to the anthropogenic influences and the impacts of changing weather regimes; this is more visible in the Pamirs. The continuous decrease in MAP populations from their natural habitat may not only negatively impact food security and traditional health systems of mountain communities, but it will make the Pamirs more vulnerable for habitation and sustenance of communities in the long run.

Inappropriate techniques for collecting medicinal plants were noted by 33% of the respondents. The interviewees explained that some of MAP collectors were nomads, grazers, and children with little or no information about the parts of plants used as medicines, active ingredients, and proper time of collection, all of which cause substantial damage to MAP populations. This assertion may not be true for the general MAP collection and marketing given that most people engaged in wild plant collection and local trades have strong indigenous knowledge about medicinal plants and the correct time of collection, processing, and marketing. However, the good practices in MAP collection need to be followed by all plant collectors. For instance, there is no need to uproot the entire plant if the leaves are the only part that contains medicinal properties. Furthermore, if the medicinal value is the roots of a plant, then it should be collected after it has matured and shed its seeds. This allows plants for regeneration.

About 20% of respondents, mostly high-profile technical people like tabibs, herbalists, homeo-doctors, and some educated people, believed that the depletion of MAPs in the natural environment is due to the change in the weather regime and climatic conditions. Increasing temperatures and reduced precipitations during the year have significantly impacted the natural vegetation in the mountain slopes and pastures in general, and MAPs in particular, due to overexploitation by local dwellers as well as medicinal plant collectors.

Other studies and researchers have found that due to a rise in temperatures, some cold-adopted alpine species are migrating upward until there are no higher areas to inhabit, at which point they may be faced with extinction (Salick et al. 2009).

Our field research indicates that most marketable medicinal plant species have been depleted in the vicinities of villages and nearby mountains. It has also become difficult to find these species in settlements 5–10 km away as they are primarily found in high mountains and pastures. These MAPs included black cumin (*Bunium persicum* Boiss.), golden root (*Rhodiola rosea* L.), stinking gum (*Ferula assafoetida* L.), black currant (*Ribes nigrum* L.), St. John's wort (*Hypericum perforatum* L.), and some species of mushrooms like morels (*Morchella esculenta* L.). Most respondents perceived this to be due to increasing biotic pressure and overharvesting by local villagers. While this may be accurate, however, recent studies in neighboring countries such as China and India illustrate that many of the local medicinal plant species have shifted to adjust to global warming in search of more suitable temperature regimes. In contrast, the species less adaptable to the effects of climate change and extreme weather-related calamities have increasingly become extinct. In the face of anthropogenic climate change, species must acclimate, adapt, or move to survive. In response, many plant species are shifting their ranges both altitudinally and latitudinally (Yin et al., n.d.).

4 Effects of Climate Change on Smallholder Farmers of Pamirs

Most of the respondent farmers believe that climate change has disturbed the local agriculture calendar over a decade. There is often drought and less rain in the spring rainy season and less snow in winter months, which has negative effects on vegetation, resulting in less herbage/forage in pastures. The weather disturbance has created more challenges for smallholder farmers in Pamir region, as sudden and untimely rains at the time of flowering damage all kinds of fruit trees upon which the livelihoods of poor farmers depend. Cold spells, even in summer month like June, cause delays in vegetation and crop production and, in some areas, new insect pests were reported on crops of economic importance.

Further, in mountainous area like Pamir region, farmers mainly depend on glacial melt water for irrigation purposes. However, due to the cold spell of weather, there is no water in the irrigation channels until the end of May and even sometimes until mid-June every year. Hence, water remains a limiting factor for subsistence farmers in the production of agriculture crops. Meanwhile, the changing climatic conditions have posed serious threats for the very survival of the mountain farmers having no and or very limited alternative options like off-farm employment opportunities for their sustenance.

5 Discussion

Results from our five-year study, consisting of field investigations and observations in the Pamirs, reveal that climate change is causing visible effects on plant population size and distribution. Further inquiry on the impacts of climate change on MAPs is needed due to the reliance of mountain communities on indigenous MAPs for livelihoods. This includes local access to safe and inexpensive traditional medicine as well as sustenance.

These findings indicate that there has been as sizable decline in the number of medicinal plants over the past 15 years. A similar finding was reported in another study from 2017 indicating that medicinal plants have been abundant 15 years ago in mountains regions and near grazing lands. However, they are now disappearing rapidly, and with each passing year, community members are forced to travel further into the mountains to gather plants necessary for their families' survival (Karamkhudoeva 2017).

Most respondents suggested that the anthropogenic pressures, including that from livestock, and unsustainable methods of harvesting to be a cause of decline in MAP availability in the Pamirs. This could be a direct result of overharvesting given the importance and benefits of the MAPs. Secondly, as MAPs primarily grow on communal lands such as forests and high mountain pastures, they are susceptible to overharvesting by villagers, local dwellers, pastoralists, and gatherers. Thirdly, incorrect, and untimely collection of MAPs disturb their regeneration. If regeneration is in jeopardy and the causative factors remain unchecked, then ultimately the plants population will drastically decline and potentially become locally extinct.

In addition to the concerns raised about the depletion of MAPs, we should also consider climate change. Although this perspective was less prominent among respondents, it was emphasized by scholars and professionals. Residents shared their experiences and observations, describing less rainfall and snow in recent years compared to 10–15 years ago. This has resulted in drought, poor forage in pastures, water scarcity in streams and channels, untimely rains damaging crops, an unaligned agricultural calendar due to changing weather patterns, and the appearance of new crop diseases and insect pests. These challenges, all of which are related to weather disturbances, may be triggered by climate change.

In summary, MAP populations are declining rapidly and shifting from lower to higher elevations. Individual interviews, community discussions, and field observations confirmed that, while medicinal plant resources were abundant in the region 15–20 years ago, these resources are rapidly declining due to natural and climatic factors. These include, but are not limited to, prolonged droughts as well as biotic and anthropogenic pressures such as over utilization of land by both humans and livestock.

Given these findings, Pamir communities should be informed about the indigenous knowledge of MAPs as well as the consequences of MAP disappearance for traditional health and food systems in mountain communities. Conservation of MAPs related to indigenous knowledge and technology transfer will help protect these medicinal plants from extinction and keep the practice of herbal medicine alive.

6 Suggestions and Recommendations

Due to the rising consciousness and self-awareness of one's health—especially in developed countries—many are turning to organic products and herbal remedies to treat various ailments in their daily lives. The promotion and processing of plant-based products have been given a fresh impetus in developed and developing countries. Thus, there is a niche for medicinal and aromatic plant products in national and international markets. This trend requires the medicinal plants and their habitat to be conserved, promoted, and sustainably managed for the benefits of mountain communities. This may be possible based on a few suggestions:

- Increase community awareness regarding the importance of conserving medicinal plants through trainings, conferences, and developing promotional materials in local languages/dialects.
- Devise a government policy focused on the conservation and management of medicinal plants and other non-timber forest products.

- Control the overexploitation of medicinal plants by residents as well as by nomads/grazers. This includes offering a pre- and post-harvest management training for people involved in medicinal plants collection and processing.
- Examine forest conversion and uprooting of shrubs from mountains.
- Identify MAPs vulnerable to climate change and cultivate them on-farm to reduce the risk of depletion or local extinction.
- Establish protected areas for MAP/biodiversity hot spots to maintain genetic diversity in the natural ecosystem.
- Practice sustainable agricultural and rangeland management to reverse land degradation in problematic areas.
- Provide training on climate-smart agriculture practices for farmers.
- Introduce deferred or rotational grazing systems within communities.
- Form community-based natural resource management committees and provide basic trainings on conservation and sustainable management of natural resources including MAPs at the village level.

7 Conclusion

Like other living organisms, plants thrive in associations and consociations in certain geographies with dominant and subdominant species. Overharvesting and depletion of any specific plant species may disrupt the entire plant community in certain area, which may threaten other species. The indigenous MAPs of the Pamirs are considered more vulnerable to changing climatic conditions and may face high risk of extinction due to their confined geographic distribution. Studies from the neighboring countries like China and India indicated that climate change is causing noticeable effects on the life cycles and distribution of high-altitude plants (Harish et al., n.d.). Besides climate change-related issues, the increasing and continued biotic and anthropogenic pressure on MAPs, with prevailing inappropriate and unsustainable collection/harvesting practices, further deteriorates the precarious conditions of MAPs in the Pamirs. The rapid depletion of MAPs from the natural environment may negatively impact traditional health systems and food security of poor mountain communities. Thus, there is a need to develop a range of participatory adaptation and conservation strategies for the larger interest and benefit of present and future generations of mountain communities in the Pamirs.

Acknowledgements This study was carried out in cross-border districts of Tajik and Afghan Badakhshans along the River Pyonj over five years. The authors gratefully acknowledge the individuals and groups of respondents in Ishkashim, Zebak, Shughnan, and Nusai districts of Darwaz Badakhshan Afghanistan and Khorog, Porshenev, Garam Chashma Ishkashim, Roshan for their generosity in sharing knowledge, information, and time during the field surveys and study.

Staff members of Area offices of Ishkashim, Shughnan, and Khorog of AKF Badakhshan Afghanistan supported us a lot in organizing individual interviews, focused group discussion, and interpretation of local dialects during the interviews, they all deserve appreciation.

We are thankful to Dr. Prof. Mohamed Behnassi, College of Law, Economics, and Social Sciences, Ibn Zohr University and Center for Research on Environment, Human Security and

Governance (CERES), Agadir, Morocco, and Prof. Dr. Mirza Barjees Baig of Prince Sultan Institute for Environmental, Water & Desert Research, King Saud University, Kingdom of Saudi Arabia for their critical insights and proofreading of the manuscript.

Collecting intensive field data and developing the manuscript would not have been possible without the financial support of the German Academic Exchange Service (DAAD), and we are thankful to DAAD for this financial support to complete this research work.

References

Adhikari L, Hussain A, Rasul G (2017) Tapping the potential of neglected and underutilized food crops for sustainable nutrition security in the mountain of Pakistan and Nepal. Sustainability 9(291):18

Aziz A (2021) Effect and impact of indigenous knowledge on local biodiversity and social resilience in Pamir region of Tajik and Afghan Badakhshan. Ethnobotany Res Appl 22:03

Booker A, Johnston D, Heinrich M (2012) Value chains of herbal medicines—research needs and key challenges in the context of ethnopharmacology. J Ethnopharmacol 140(1):624–633

Harish BS, Dandi SB, Umesha K, Pallavi HM (n.d.) University of Horticultural Sciences, Bagalkot, Karnataka. Impact of climate change on medicinal plants—a review. https://www.researchgate.net/publication/233897401_Impact_of_climate_change_on_Medicinal_Plants

ICARDA (2006) Medicinal and aromatic plants as alternative livelihood sources for rural communities in Afghanistan. Jerba, Tunesia

Jeppesen AS, Kristiansen U, Soelberg J, Jager A (2012) Antihistamine effect of *Rubia tibetica*, used to treat anaphylaxis caused by tick bites in the Pamir Mountains, Afghanistan. J Ethnopharmacol 141:1077–1079

Karamkhudoeva M (2017) Revitalization and retention of indigenous knowledge of medicinal plants in Afghanistan CAARF project policy brief

Karamkhudoeva M, Laldjebaev M, Ruelle ML, Kassam K-A (2021) Medicinal plants and health sovereignty in Badakhshan, Afghanistan: diversity, stewardship, and gendered knowledge. https://rdcu.be/cBQhb

Kassam K, Karamkhudoeva M, Ruelle M, Baumflek M (2010) Medicinal plant use and health sovereignty: findings from the Tajik and Afghan Pamirs. Hum Ecol 38(1):817–829

Kassam KA, Baumflek M, Ruelle M, Karamkhudoeva M (2013) Nurturing knowledge: medicinal plants in the Pamir Mountains of Afghanistan and Tajikistan. Conservation Bridge, case study no 17. Retrieved from Herring J (Producer) (2012) Nurturing knowledge: medicinal plants in the Pamir Mountains of Afghanistan and Tajikistan. Video no 17. Conservation Bridge. Retrieved from http://www.conservationbridge.org/casestudy/nurturingknowledge

Kruse W (2015) Competitive market assessment report for Sea-buckthorn and Liquorice in Afghanistan. USAID/Aga Khan Foundation. Kabul, Wilhelm Kruse

Moheb Z, Mostafawi SN (2012) Biodiversity reconnaissance survey in Darwaz Region, Badakhshan Province, Afghanistan. WCS Monitoring & Evaluation Team, Afghanistan. Wildlife Conservation Society, Bronx

Rasul G, Hussain A (2015) Sustainable food security in the mountains of Pakistan: towards a policy framework. Ecol Food Nutr 54(6):625–643

Salick J, Fangb Z, Byg A (2009) Eastern Himalayan alpine plant ecology, Tibetan ethnobotany, and climate change. Glob Environ Change 19(2):147–155

Sher H, Aldosari A, Ali A, de Boer HJ (2014) Economic benefits of high value medicinal plants to Pakistani communities: an analysis of current practice and potential. J Ethnobiol Ethnomed 10(1):1–16

Soelberg J (2016) Useful plants of Wakhan and Pamir. Habibullah Haseeb, Kabul, Afghanistan

WFP (2017) Climate risks and food security in Tajikistan: a review of evidence and priorities for adaptation strategies

Yin L, Zachary M, Zheng M (n.d.) Abstract: the traditional medicine knowledge and medicinal plant species move in response to climate change adaptation in Tibetan village of Eastern Himalayas. China. http://www.speciesonthemove.com/3603

Ali Aziz As a Research Fellow, Aziz is associated with the Mountain Societies Research Institute (MSRI), University of Central Asia (UCA), Khorog, Tajikistan, for over four years. He has 25 years of professional experience in rural development and strategic and participatory planning, with a special focus on food security and livelihoods improvement. His work in natural resource management has included projects in agriculture, forestry, rangelands/livestock, watershed, and participatory management of water resources in the Panj Amu river Basin in Tajikistan and Afghanistan. Much of the time, Aziz has employed participatory approaches that help empower local communities. Aziz also has conducted research on the above themes in Pakistan, Afghanistan, and the Pamir region of Tajikistan—providing him with much first-hand experience with rural mountain communities. Aziz was awarded the prestigious South Asia Fellowship 2017 from Cornell University for his work on "Vulnerability and Disaster Risk Assessment in the Emerging Scenario of Climate Change in North-Eastern Afghanistan". Aziz holds a Professional Master's degree in Natural Resources Management from the International Institute for Aerospace, Survey, and Earth Science in the Netherlands, and an MSc in Botany and Forestry from Peshawar University, Pakistan. Currently, Mr. Ali is pursuing his Ph.D. degree at Philipps Universität, in Marburg, Germany.

Mrs. Munira Karamkhudoeva holds an M.Sc. in Entomology from Tajik University and is now pursuing her Ph.D. degree at Philipps Universität, in Marburg, Germany. As a Biologist/Entomologist, Mrs. Karamkhudoeva is associated with the Pamir Biological Institute (PBI), Khorog, Tajikistan for over 15 years and has a rich professional experience in the field of biological research in Afghan and Tajik Badakhshan. Besides her expertise and contribution in entomology, particularly in promoting integrated crop management and biological control mechanisms, she conducted studies on medicinal and aromatic plants in the Pamir region of Tajik and Afghan Badakhshans. She was awarded Central Asia and Afghanistan Research Fellowship (CAARF) by the University of Central Asia (UCA) back in 2016–17. Mrs. Karamkhudoeva worked for over 5 years as a Consultant Biologist/Entomologist for the Aga Khan Foundation (AKF), Badakhshan, Afghanistan during 2012–16. She also worked as a Consultant Researcher for the Mountain Societies Research Institute (MSRI), University of Central Asia and conducted a study on market assessment medicinal and aromatic plants in Tajikistan and Afghanistan during 2017–2018. She has several international publications on medicinal plants and human health sovereignty in the Pamir region of Tajik and Afghan Badakhshans.

Dr. Michael Keusgen is a Professor at the Philipps-Universität Marburg, Germany. He studied pharmacy at the Rheinische Friedrich-Wilhelms-Universität Bonn between 1984 and 1988. After internships in public pharmacy and industry (Bayer Company), he gained his Ph.D. degree in 1993 with a research project about polyphenolic compounds in brown algae. Between 1993 and 1994, he spent one year as a research fellow at the National Research Council of Canada, Halifax. From 1994, Dr. Keusgen established his own research group focused on biosensors and natural products research. In 1999, he got his habilitation and in 2003 a professorship for bioanalysis at Philipps-Universität Marburg. Since 2007, he acts continuously as the Dean of the Faculty of Pharmacy and was also a member of the Board of Trustees of the same university for several years. Since 2003, annual botanical field trips were made into countries of Southwest and Middle Asia in order to investigate medicinal plants there. Recently, a book about the medicinal plants of Afghanistan has been published under his name. Dr. Keusgen is an expert of the European Pharmacopoeia and

acts as the Chair of a working group of this Pharmacopoeia. He is also a member of the German Pharmacopoeia as well as the President of a commission of the German government dealing with the legal status of herbal drugs as well as dietary supplements. In Germany, Europe and Asia, he is a well-known specialist for medicinal plants and their preparations, especially essential oils, and acts as a reviewer in questions related to medicinal plants at German courts.

Burgeoning Desert Locust Population as a Transboundary Plant Pest: A Significant Threat to Regional Food Security

Tasneem Ahmad, Keith Cressman, Ijaz Rasool Noorka, Marwa Ben Omrane, and Mohammad Katbeh Bader

Abstract Desert locust, *Schistocerca gregaria* (Orthoptera: Acrididae), is a spectacular example of nature but also a menacing scourge. Its breeding area extends from Morocco to Pakistan and India. Unprecedented movement and migration of desert locust occurred during the current upsurge of 2019–2021. It has migrated and invaded green crops up to Nepal during this gregarious phase. For monitoring, forecasting, and early warning of desert locust in the countries where the crops are under direct threat of this pest, FAO established the Desert Locust Information Service (DLIS), nearly five decades ago. DLIS has a state-of-the-art technology, a very unique expertise, and field presence with the ability to link up different governments to strengthen their capacities in desert locust management. The right to food is a human right, and food needs to be available, abundant, and accessible to all. The current COVID-19 pandemic, in amalgamation with desert locust, has created an extraordinary situation that has shaken the food security and economy of the whole region (from Morocco to Pakistan and India). In the wake of this pandemic, we need to find out the prudent ways to fight this scourge by our own resources in collaboration with the FAO-based contingency plans. Proper control and management of desert locust in the region under direct threat are needed in order to save the crops from damage and ensure food security.

T. Ahmad (✉)
General Department of Plant Protection (DPP), Karachi, Sindh, Pakistan
e-mail: tasneem91@yahoo.com

K. Cressman
Plant Production and Protection Division, Food and Agriculture Organization (FAO), Rome, Italy
e-mail: Keith.cressman@fao.org

I. R. Noorka
Department of Plant Breeding and Genetics, University College of Agriculture, University of Sargodha, Punjab, Pakistan

M. B. Omrane
National Agronomic Institute of Tunisia (INAT) and Mediterranean Agronomic Institute of Montpellier (CIHEAM/IAMM), Montpellier, France

M. K. Bader
International Phytosanitary Expert, Amman, Jordan

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_10

Keywords COVID-19 pandemic · Desert locust · FAO · Food security · Forecasting · Monitoring

1 Introduction

Food is the basic necessity of life for human beings and animals. It consists of animal or plant origins composed of nutrients in the form of proteins, carbohydrates, and minerals, which are necessary for metabolism and support physical growth and development (Noorka 2019). The right to food is a human right, and food needs to be available in abundance and accessible to all (FAO 2020a, b, c, d). The term 'food security,' which is academically and thoroughly defined, exists when 'all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life' (FAO 1996). Conversely, food insecurity occurs when physical, social, or economic access to adequate food is denied to people. Similarly, it has been stressed by the FAO that food security is a multidimensional aspect directly associated with the political actions at different scales. These actions must ensure a state like the global food security, which is based on five pillars including obtainability of healthy food, accessibility to food, consumption of food, permanency in supply of food, and evading malnutrition (Noorka and Heslop-Harrison 2019a, b). Subsequently, food insecurity is about the perils and uncertainty which require investigation of continuing malnutrition and severe insecurity that imitate economic poorness and instability of food system, thus leading to acute poverty.

Enhancing food security requires as well the consideration of other important dynamics, including climatic variability, sources of supply of healthy food and its distribution within poverty-stricken countries, and different forms of insecurity in food. The entitlement to human rights pertaining to food has given a very narrow definition to food security, which is dangerously close to chronic poverty. Due to the high demographic growth in most developing countries, in addition to other factors, sustainable food security is still a real challenge for researchers and service providers.

2 Challenges to Food Security

Achieving and maintaining food security are objectives which are increasingly challenged by many factors, such as:

- The rapidly expanding world population, especially in developing countries, which is anticipated to surpass 9 billion by the mid of this century (FAO 1996; Noorka and Heslop-Harrison 2015);
- The considerable increase in rural to urban migration with some urban areas expected to host up to 70% of the world population by 2050, again mostly in developing world (in contrast of current 49%);

- The changing food consumption patterns due to the economic growth, globalization, and urbanization (FAO 2017);
- Natural resource scarcity due to increased human activities and different pressures;
- Frequent anomalous environmental and climatic changes, including recurrent disasters and emergencies; and
- The negative impacts of globalization which are affecting farming systems, food trade and access to food markets, the availability of land for food production, and market information about food prices (FAO 2017).

Furthermore, the recent plague-like situation that occurred due to desert locust breeding and migration is yet another shock that severely jeopardizes the food security in the affected region. This problem is further developed in the next section.

2.1 Desert Locust, a Bigger Threat?

The competition for food and shelter among human beings and insects is incredibly ancient. This competition has existed for centuries even before civilization. Among such insects, desert locust *Schistocerca gregaria* (Forskål 1775) (Orthoptera: Acrididae) is a spectacular example of nature but also a menacing scourge. This notorious pest is known as the most dangerous migratory insect on our planet that can cause widespread damage due to its rapid and prolific multiplication, long-distance migration, and voracious eating habit. The impact of locust swarms on human population is known for centuries and has remained a main challenge to food security throughout the world. In numerous African countries, locust outbreak is considered one of the main severe threats to agricultural productivity. In Senegal for example, this risk is ranked second after drought (D'Alessandro et al. 2015). The remarkable ability of locust swarms to swiftly migrate long distances and appear suddenly out of nowhere in great numbers has given the pest a mysterious reputation. Perhaps for this reason, locusts are considered as a curse or divine punishment and are described as the most havoc causing plagues of Egypt in both the Bible and the Holy Qur'an (El-Mallakh and El-Mallakh 1994).

Diversity in Locust Species

Out of the approximately 6800 species described of Acrididae/grasshoppers (Cigliano et al. 2017), nineteen are presently referred to as locusts (Cullen et al. 2017). The locusts are essentially from the grasshopper family but they are capable to exist in two different phases: a solitarious phase (hopper or adult) and as part of a gregarious phase consisting of nymphs (hopper band) and adults (swarm), depending on specific environmental conditions (Cullen et al. 2017; Pener 1991). While these two phenotypes vary in morphology, physiology, and behavior, their characters can be dissimilar and vary among different locust species. Within a few hours, the behavior of a locust can change; however, it takes at least two generations to complete a morphological shift from one phenotype to another. This flexibility, which is named *phase polyphenism* of locusts (Pener and Simpson 2009; Pener 1991), creates exceptional challenges for tackling them. After breeding and originating from a zone gregarious phase, desert locust can swiftly fly up to 150 km during a single day and such locust swarms are capable of spreading across countries, regions, and continents (Draper 1980).

The desert locust is reported to affect agricultural crops in some 60 countries (Popov et al. 1991). A single swarm of locust has the ability to cover several hundreds and thousands of square kilometers of area (Mohamed Shaluf 2007). In early 2020, one swarm in northern Kenya measured a size that covered 20 km × 40 km, an area equivalent to the country of Luxembourg in Europe. Swarms are not limited to one country or region but can easily spread over many continents.

A swarm can breed in vast, often remote areas, and can migrate to other far-flung regions in search of food and places favorable for its breeding. It is said that there is no king or queen in a locust swarm, but it moves in a disciplined way. Perhaps the locust swarm maintains a unified cohesion on the basis of specific pheromones excreted by all individuals to keep the gregarious phase intact from a generation to another. A recent research on *Locusta migratoria* by Guo et al. (2020) has confirmed that pheromones secreted by individual locusts bind them together for gregarious activities. The authors show that the 4-vinylanisole (a compound) can trap locusts by aggregating them into concentrations. The research has also confirmed that gregarization occurs as a result of a specific compound or certain pheromone developed in the insects' brain. Therefore, the brain chemical, serotonin, was determined to be the causal agent of the gregarious phase in desert locust, while in the migratory locust, it enhances the solitary phase. The swarming process of desert locust involves a phenomenon recognized in phase polyphenism that is affected by environmental changes including food deficiencies and micro-climatic concentrating mechanism, which influence modifications in the morphology (size and color), behavior, and physiology of the locust. Such a phenomenon is named *phenotypic plasticity* in insects and animals. The gregarious phase of desert locust leads to upsurges and plagues, which cause crop devastation, resulting in colossal food loss and famine.

Desert Locust as a Dangerous Migratory Pest

The desert locust is the world's most dangerous and deadliest migratory pest of agricultural economies. Its breeding area covers up to sixty countries in Africa and Asia, which is equivalent to about 20% of the earth's land surface. It is a voracious feeder that can be a direct threat to food production and security in a very large region extending from North Africa to Southwest Asia, including parts of the Middle East (Fig. 1). Locust, which lives and breeds in semi-desert and desert areas, is a serious insect pest due to its habit of swarming and voracious feeding. It inflicts grave damage to agro-pastoral production during gregarious swarming and invasion periods, thus subsequently disturbing the socio-economic and ecological outcomes

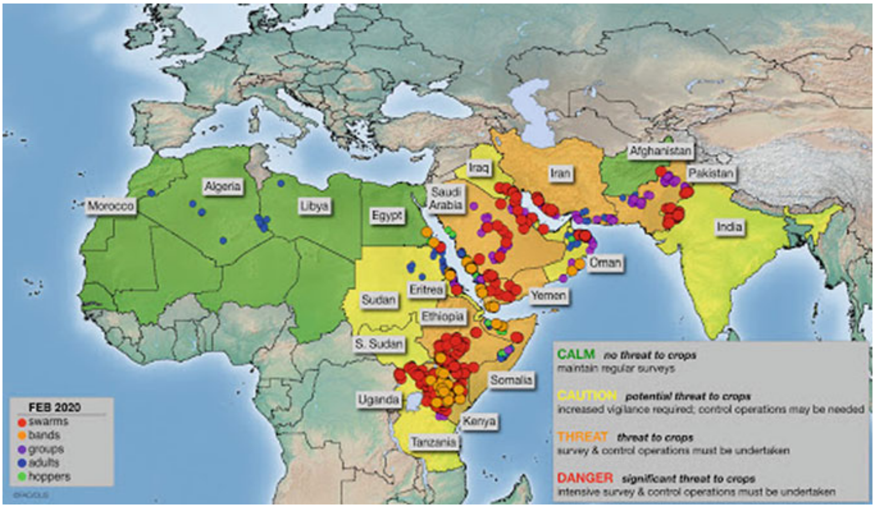


Fig. 1 The global desert locust situation in February 2020. *Source* FAO/DLIS

(Lecoq 2003). Locust outbreaks, upsurges, and plagues develop from time to time and are associated with periods of increased rainfall and favorable environmental conditions for breeding.

In most years, solitarious locust populations are normally present and scattered within the very large recession area between West Africa and India, but in very low and insignificant numbers and often distant from agricultural production areas. The recession area covers about 16 million km^2 and is mostly prevalent in the Sahara, Arabia, and southwest Asia deserts. Within this area, small outbreaks can occur after a sufficient rainfall and a successful breeding. If not controlled, this can lead to much larger upsurges and plagues during which gregarious populations can expand to a bigger area of up to 30 million km^2, comprising at least 65 countries in Africa, the Middle East, and Southwest Asia, and including broadly cultivated regions that are inhabited by more than one billion people (Lecoq 2003). Gregarious desert locust is extremely voracious. Every km^2 of desert locust swarm contains some 40–80 million insects (FAO 2020).

Desert Locust Plagues

Desert locusts are omnivorous and capable to consume all types of green vegetation, thus causing damage to food crops as well as pastures on which farming and herding families depend. A swarm's hunger is ravenous: For example, a swarm the size of New York City can eat the same amount of food in one day as everyone living in the states of California and New York (FAO 2020a, b, c, d). In one day, a single square km^2 of swarm is capable of consuming the same quantity of food as consumed by 35,000 people (FAO 2020a). As swarms are frequently tens, hundreds, or even thousands of square kilometers in size, their consumption can have a devastating impact on crops and pastures. Moreover, migrating swarms can cover long distances, easily spread from one continent to another across different seas and oceans. Research has shown that gregarious locusts multiply 20-fold with each generation that normally lasts about three months; such an increase is exponential since at the end of a year there can be 160,000 times more locusts.

In the past and in the absence of any control measures, desert locust plagues have frequently developed and continued uninterrupted for decades if not longer, and the calmer recession periods had shorter durations. Since 1860, there have been eight plagues with at least one lasting 14 consecutive years: 1860–1867, 1869–1881, 1888–1910, 1912–1919, 1926–1935, 1940–1947, 1949–1962, and 1987–89. In addition, there have been regional upsurges in 1992–1994, 1994–1996, 1996–1998, 2003–2005, and finally 2019–2021 (Lecoq 2003; van Huis et al. 2007; FAO 2020a, b, c, d). The last upsurge (2019–2021), with its origins in 2018, once again reminds us of the economic importance of desert locust and the need to rapidly strengthen national locust programs, update management strategies, and reinitiate international cooperation if we are to avoid this historical menace from threatening food security and livelihoods.

Cyclones and Unabated Breeding of Locust

The current upsurge developed from two cyclones, which brought heavy rains providing suitable breeding condition, resulted in three consecutive generations of successful unabated breeding of locust from mid-2018 to early 2019. This caused an 8000-fold increase in locust numbers that could not be controlled. Numerous swarms formed from the breeding areas of the Empty Quarter deep in the Arabian Peninsula invaded many nations including India, the Islamic Republic of Iran, and Pakistan, as well as the East Africa and the Red Sea area. Several unprecedented movements and migrations of desert locust took place during the 2019–2021 upsurge. For example, spring-bred swarms invaded the areas from southern Iran and southwest Pakistan to the Himalayan foothills in Nepal, an event that has not occurred in more than a half century. In late 2019, other swarms invaded Kenya, a country which has not faced such an invasion during the last 70 years ago. Swarms appeared in neighboring South Sudan, Uganda, and Tanzania for the first time since the early 1960s. At least one swarm reached northeastern areas of the Democratic Republic of Congo where swarms were last seen in World War II.

3 FAO's Role in Fighting Desert Locust

One of the FAO's core mandates is the monitoring, forecasting, and early warning of desert locust in affected countries through the Desert Locust Information Service (DLIS), which has been in operation for almost five decades. It has state-of-the-art technologies and a unique global expertise. Its well-known field presence has the ability to link up governments from different countries to strengthen their capacities in desert locust monitoring and early warning. In addition, the FAO has established three regional locust commissions that focus on strengthening national capacities of affected countries in surveying, control, reporting, training, contingency planning, and other aspects of desert locust management. The Commission for Controlling the Desert Locust in South-West Asia (SWAC) is the FAO's oldest regional locust commission, established in 1964, and has four member countries: Afghanistan, India, Iran, and Pakistan. The SWAC's Executive Secretary is the Senior Locust Forecasting Officer stationed in Rome at FAO HQ. The Commission for Controlling the Desert Locust in the Central Region (CRC) was established in 1967 and has 16 member countries: Bahrain, Djibouti, Egypt, Eritrea, Ethiopia, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Sudan, Syria, UAE, and Yemen. Its Executive Secretary is posted at the FAO regional office in Cairo, Egypt. The Commission for Controlling the Desert Locust in the Western Region (CLCPRO) consists of ten countries in West and Northwest Africa: Algeria, Burkina Faso, Chad, Libya, Mali, Mauritania, Morocco, Niger, Senegal and Tunisia. Its Executive Secretary is stationed in Algiers, Algeria.

Since 2019, numerous desert locust swarms have been destroying different food and pasture crops and paralyzing human societies inhabiting the Africa's Greater Horn, the Arabian Peninsula, and the Indian subcontinent. The DLIS continuously warns that locust populations could multiply a further 20-fold during the coming months if intensive control efforts are not maintained. This could be further exacerbated by widespread rainfall resulting from cyclones such as the unexpected Cyclone Gati that brought a year's worth of rainfall to northeast Somalia in two days during November 2020. Such extreme weather events create a favorable breeding environment for locusts that can last six months or the equivalent of two generations of breeding and a 400-fold increase. The FAO has warned that, in the absence of effective survey and control operations, this could lead to a possible food disaster.

3.1 Famine Early Warning Systems Network

Additionally, the Famine Early Warning Systems Network (FEWSNET), a provider of early warning and analysis on food insecurity created by the US Agency for International Development (USAID), reports that several African countries affected by desert locust—including Yemen—are presently experiencing different levels of food insecurity comprising of 'stressed,' 'crisis,' and 'emergency.' This classification of acute food insecurity is based on combining different indicators connected with food consumption, livelihoods, malnutrition, and mortality among the population.

During the annual winter breeding period, desert locust activity can often be dangerous along both sides of the Red Sea, including Yemen and Saudi Arabia. Saudi Arabia is in a relatively better position due to a well-established and functioning national locust program and a robust economy and therefore has reportedly a lower risk score of 8.5 on the Global Hunger Index. On the other hand, Yemen faced much higher risks of stressed, crisis, and emergency levels of food insecurity, especially during the last quarter of 2020 as indicated by FEWSNET.

Similarly, the World Food Programme (WFP) suggests that rice, wheat, and flour prices are at 'stress' and 'alert' levels in many local markets of the locust-affected region. Yemen was expected to experience the worst food crisis in 2020–2021 due to the combining effects of existing conflict, economic crisis, climate-related shocks, and attack of different insect pest desert locust and fall armyworm (WFP 2020). However, the countries listed above are not the only ones whose food systems could suffer from the invasion of locust swarms and outbreaks of other pests. These food insecurity and existing hunger problems indicate potentially severe impacts on population.

A greater number of cyclones and remarkably rainy weather have occurred in East Africa as a result of a positive Indian Ocean Dipole that pulls warmer water toward the Horn of Africa and Arabian Peninsula. A recent research study published in *Nature* has shown that such events arising from a positive dipole are occurring more frequently. Hence, climate change could lead to a more often rapid warming in the western Indian Ocean, which subsequently yields stronger and more frequent cyclones in the Horn of Africa. Ultimately, such favorable conditions will definitely support ideal breeding grounds for desert locusts in the region. In this way, locust outbreaks could become a more frequent and dangerous risk to food security in East Africa if swift and effective anticipatory action and response measures are not put into place in the region.

3.2 An Estimation on Hunger and Food Security

A large-sized desert locust swarm is capable of devouring up to 1.8 million metric tons of food consisting of green vegetation, food equal to being sufficient to feed 81 million individuals. Such swarms are intimidating large pasture and crops areas in many affected countries. The FAO has reported that the current upsurge is the worst in last two and a half decades in eastern African countries of Somalia and Ethiopia and the worst situation in 70 years in Kenya. This is a classical global single upsurge, and if this locust upsurge reaches plague levels, then it could extent to twenty percent of land mass of the earth (World Bank 2020a, b). A situation like this could result in food insecurity in Africa, the Middle East, and the Indian subcontinent. This situation could give rise to the likelihood of making 24 million people insecure for food availability, which may result in the internal displacement of some eight million people within the region. Any further expansion of locust infestations would threaten food security, including the often-overlooked risk to pastures for livestock survival and milk production. Such adverse impacts on the food web in the region could harshly threaten livelihoods by eroding people's savings and pushing them toward poverty. During the last desert locust upsurge in 2003–2005, the response cost was more than half a billion US dollars while crop associated damage was estimated at approximately $2.5 billion.

The current locust upsurge is amazing and unprecedented because it coincides with prolonged and persistent rainfall that is favorable for both swarm breeding and crop production. However, when swarms form and invade at critical times in the planning season such as sowing and harvesting, the hard efforts of the farmers can be devastated easily. The situation can disrupt the livelihoods and negatively impact the survival of farming families and communities during the current season and years to come. Conservative estimates for locust-related losses, including those to food crops, livestock, etc., are estimated to the tune of US $8.5 billion for countries in the wider East African region, Djibouti, and Yemen, if control measures are not undertaken effectively and on time. A recent joint impact assessment by the FAO and the Ethiopian Government found that the country faced an estimated cereal loss of 356,286 metric tons, along with destruction of 197,163 ha of cropland and 1,350,000 ha of pasture lands, resulting in more than 1 million Ethiopians in need of food assistance.

3.3 The World Bank's Initiative

Keeping this grave situation in view, the World Bank Group has already provided US $500 million of support to countries in the Horn of Africa and the Middle East that have been invaded by locust swarms. This support was primarily intended to help the affected populations secure their immediate food needs. Later on, the focus was rather on the rehabilitation of food production and the maintenance of livelihoods in order to empower the communities under stress, in addition to strengthening national locust survey and control programs to respond to future locust threats.

Djibouti, Ethiopia, Kenya, and Uganda are the hardest-hit countries, which are financed under the initial phase of the World Bank program, with a total funding package of US $160 million. Additionally, the World Bank is financing national locust programs with funds of US $25 million for Yemen, US $200 million for Pakistan, and US $40 million for Somalia. Similarly, a reallocation of US $13.7 million for Kenya has been already made by the Bank to cover emergency locust survey and control operations. The emergency financing of US $600,000 to help control locust infestations by affected communities in Djibouti is planned (World Bank 2020a, b).

According to the World Economic Forum (Charlton 2020), the current locust upsurge is one of the most serious that has happened in the last 70 years and it could endanger almost five million people facing starvation in East Africa, as reported

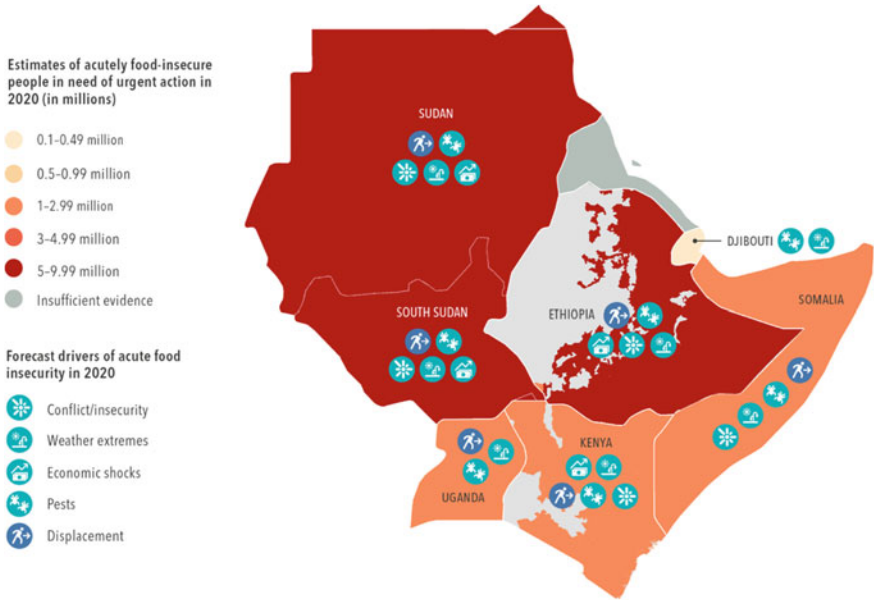


Fig. 2 Food insecurity drivers. *Source* Food Security Information Network[1]

by the International Rescue Committee. Locusts have destroyed crops in Kenya, Uganda, South Sudan, Ethiopia, Somalia, Eritrea, Djibouti, and Sudan, which are the epicenter of the worst-hit countries in the region.

Reportedly, about 20% of the world's extremely food-insecure population are living in the IGAD region—which includes Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, Sudan, and Uganda—covering a large area of 5.2 million square km (FAO 2020b) (Fig. 2).

3.4 Substantive Risk

If the current locust plague is not controlled effectively and on time, there is a substantive risk that expenditures of hundreds of millions of dollars will multiply further and it can take years to bring it back under control (FAO 2020a, b, c, d). The FAO predicts a cereal crop loss in the worst case up to 50–70%, or up to 20–30% loss in the best control case, subject to any infestations that remain untreated. Estimates by the IRC suggest that undertaking the necessary emergency operations in Somalia alone requires supplementary funds of $1.98 million in 2020.

[1] https://mcusercontent.com/9206ea93bb8c6f35f98cc8ccf/files/9ccee662-81c6-444a-9a91-6ff375f7c95e/IGAD_RRFC_2020_Official_Launch_Slides.pdf.

According to FAO, 20.2 million people are currently facing acute food insecurity in African countries, including Ethiopia, Kenya, Somalia, South Sudan, Tanzania and Uganda, and this number could possibly expand rapidly due to the simultaneous impacts of the desert locust influx and the COVID-19 pandemic (FAO-WFP 2020). The FAO Director-General (2020) has reported that substantial successes have been achieved in the current desert locust upsurge in East Africa and Yemen, yet more efforts are needed to protect food security. According to preliminary estimates, about 720,000 tons of cereal, which is sufficient to feed five million people a year, has been saved in different ten countries by foiling desert locust attacks. Additionally, some 350,000 pastoral households have been secured from damages. Even after spraying huge areas of first-generation locusts, a second wave of locust hoppers and fledglings is likely to emerge during the coming months in East Africa when crops would be ready for harvesting. The existing upsurge was quite disturbing for the East Africa region.

The FAO's appeal of $311 million in emergency funds for West Africa, the Horn of Africa, Yemen, and southwest Asia in 2020 illustrates the seriousness of the threat to food security due to locust breeding and invasion in the region. The appeal covers control operations as well as support for livelihood activities. The FAO continues to play its instrumental role in appealing to international partners and coordinating assistance to different governments for chemical and biopesticides, sprayers and other equipment, technical experts, training, and even aircraft. As a result of these efforts, more than 2.8 million ha were treated against desert locust infestations in 22 countries of Africa, the Middle East, and southwest Asia. Of this, more than 1.5 million ha were treated in the Greater Horn of Africa and Yemen by ground and aerial operations, including 28 aircraft and more than 6000 flying hours. These efforts saved 3.1 metric tons of crop production, which is enough to feed 18 million people for one year. In addition, the loss of 619,000 L of milk production was averted. More than 200,000 households were provided with livelihood assistance and crop packages. In all, the livelihoods and food security of some 28 million people were protected in 2020. The economic benefit of these interventions is estimated to be $1.2 billion.

In May 2020, the FAO predicted that, if left uncontrolled, the threat of locust invasions in Pakistan could cause estimated potential losses of about $2.6 billion to winter crops such as staple food wheat and near $3 billion to summer crops, including rice and cotton.

The total GDP of Pakistan was $284 billion in 2019 when the country witnessed the worst locust infestations in decades and farmers described the extensive damage of crops in agricultural areas (IMF 2020). According to initial FAO estimates, the potential to food crop losses is nearly 5 billion dollars in Pakistan (Dawn 2020).

3.5 Colossal Scale, Urgency, and Complexity of Current Desert Locust Crisis

Keeping in view the colossal scale, urgency, and complexity of current desert locust crisis, the FAO has recently declared a corporate thematic scale-up for desert locust in early January 2020 and activated fast-track procedures. The FAO response to food chain emergencies, like pests and animal and plant diseases, is managed by the Food Chain Crisis Management Framework. Hence, the current locust response is actively manned by the Emergency Centre established for Transboundary Plant Pests (ECTPP), which integrates the operational and technical capacities of the Plant Production and Protection Division (NSP) and the Office of Emergencies and Resilience (OER), under the overall management of Deputy Director-General for Operations.

In the wake of the COVID-19 pandemic, appropriate response mechanisms to fight the scourge through self-mobilized resources, in collaboration with the FAO based on contingency plans for locust control to safeguard food security in the region, are needed. It is, however, important to include the lessons learned from the 2019–2021 upsurge and invasions of desert locust throughout the world, which have occurred on epidemic proportions, resulting in food insecurity and increased hunger of populations living in the affected regions. First of all, it is clearly recognized that coordinated and integrated efforts are direly needed to control the menace.

Each country should assume its full responsibility in taking all possible control measures within their geographical territories on time and in a most effective manner. National efforts need to be well-coordinated under the auspices of FAO's global Desert Locust Control Committee because the pest is migratory in nature and its rapid and widespread invasion can give rise to food loss and hunger within damaged areas. Hence, resources from all members along with expertise and technology are needed to undertake effective measures in the locust breeding areas. The successful control of locust upsurges depends on regular monitoring in the breeding areas of the deserts, early warning coupled with anticipatory action and timely control measures. If a swarm is not detected on time, it can play havoc with food and other crops by leaving grave effects on livelihoods in the affected region. Early detection is enabled through regular monitoring and timely reporting of high-quality data. Identifying the locations of desert locust and noting their stage of development are critical to informed response actions for a maximum impact.

FAO has supported national survey and control teams by developing innovative, cutting-edge technology tools. One such tool is eLocust3, a rugged handheld tablet, that survey and control teams' use in the field to collect and transmit data in real time via satellite to their national locust control center where it is then forwarded to DLIS in Rome. These data, along with remote sensing imagery, weather information, and historical records, are used within the country to analyze the current situation in order to make further operational and planning decisions concerning survey and control operations. DLIS also analyzes these data to assess the current situation and forecast the scale, timing, and location of locust breeding and migration. In this way, the DLIS provides early warnings and alerts to affected countries so that they have as much time as possible in advance to undertake the necessary preparations and response. Since 1978, the DLIS continues to issue situation bulletins and six-week forecasts every month.

Strengthening the national capacity of stakeholders to conduct robust survey activities is critical. This includes not only training of government staff but also of community focal points residing in potential locust breeding areas so that they can alert the government about locust sightings and movements. In any national locust programs, it is important to involve communities, primarily in locust reporting, and ensure their participation as an integral part of the national system.

It is also imperative to promote locust control measures that are safe to the health of humans, animals, and the environment. FAO follows strict attention in this regard by applying corporate protocols developed to avoid contamination and adverse effects of locusticides and other materials. Assessments focus not only on locust control operation efficacies and locust impacts on crop production and livelihoods but also on the associated potential health and environmental impacts. In addition to imparting training on the safe handling of pesticides, proper storage and transportation, the safe disposal of containers and drums, and the appropriate use of personal protective equipment are implemented. During desert locust control campaigns, FAO conducts impact assessments to monitor and safeguard farmers, herders, other inhabitants, and the environment.

4 Innovation and New Technologies in Combating Desert Locust

FAO has successfully adopted and applied a number of IT technologies to further enhance and improve desert locust monitoring, reporting, early warning, and control. As previously mentioned, eLocust3 was developed in 2014 and operates on a rugged handheld tablet that is used by well-trained and experienced national locust teams in more than 25 countries. During emergencies, additional teams from other national agencies are often seconded within these countries as well as other countries that do not have eLocust3. For this reason, FAO developed a mobile phone (eLocust3m) and GPS (eLocust3g) version in 2020 so that this tool could be extended to seconded teams as well as to the general public for crowd-sourcing information. While the tablet version collects possible data concerning habitat conditions, locusts, and control operations, the mobile and GPS versions collect only the very basic data about locust type and hectares affected. In this way, new users require very little training or expertise to use these two new versions. In general, eLocust3 data are the foundation and basis for undertaking survey and control operations in the field, planning future actions, assessment of the situation, and forecasts for early warning. The eLocust3 data are managed and analyzed within a custom geographic information system, RAMSES GIS, that has been developed by FAO and is in use by nationally designated locust information officers in each frontline country. RAMSES exports eLocust3 and other data for ingestion by the SWARMS GIS used by DLIS to monitor and assess the global situation.

4.1 The Use of Remote Sensing

Remote sensing imagery is used by countries and DLIS to estimate rainfall, green vegetation, and soil moisture. FAO has developed two remote sensing products, one that is a dynamic greenness map to show the onset of green annual vegetation after rainfall and a second one that detects surface and sub-surface soil moisture necessary for locust breeding. In addition, DLIS makes use of a trajectory model to estimate swarm migration routes and a breeding model to estimate development rates of locust eggs and hoppers. Lastly, FAO has been developing drone technology to supplement surveillance efforts and to consider it as another potential platform for control to supplement ground and aerial control.

At present, a fixed-wing survey drone is available to be used by survey teams that can be launched in the field to identify areas of green vegetation up to 100 km away. The results are processed on board and delivered to the eLocust3 tablet so teams can navigate specifically to those areas for checking if locusts are present by using the drone at each particular site. The drone can also be used to survey in accessible areas such as sand dunes. For control, further field testing is required to establish standard operating procedures and technical guidelines before drones can be used safely and effectively to treat locust infestations. Nevertheless, it is clear that the use of drones in desert locust control will be limited to those areas that cannot be easily treated by ground and too small to be treated by an aircraft, such as a small swarm roosting on individual treetops. Limited battery life and load capacity will restrict the use of drones for large-scale control operations. In addition, it is anticipated that the unit area cost of treatment by a drone will be significantly higher than that by ground and aircraft.

5 The Way Forward and Conclusions

In order to improve the management of desert locust so that it is effective, efficient, and sustainable, ownership by national authorities will be critical as an initial step. This requires the so-called buy-in from the central administration within a country as well as state and local entities. A centralized mechanism should be established so that a well-coordinated and systematic response can be achieved at the central and local levels within a country. For this to occur and to be maintained especially during calm years, the national program should be institutionalized, ideally within the national legal framework. Such a program should have a special line item within the annual national budget to ensure that adequate funds are available and earmarked for the sole use in desert locust activities.

The roles and responsibilities of all actors should be clearly defined. The national locust program should be overseen by a director and supported by deputies as needed. For example, at least two persons should be designated to manage and analyze all survey and control data as well as remote sensing imagery and to prepare situation updates. Teams in the field should be designated for survey and control operations and a mixed search-and-destroy function.

A strong national capacity to provide training to the competent staff should be established. With the help of FAO, designated National Master Trainers should be equipped with locust knowledge and training skills so that they can provide continuous training on survey, control, reporting, and pesticide safety to field teams in local languages. Every field team should be equipped and use one of the eLocust3 suite of tools for real-time reporting. Sufficient equipment in good working conditions such as vehicles, sprayers, camping and training material, chemical and biopesticides, and spare parts should be available in appropriate quantities to meet the needs. Inventory systems should be established and kept up to date to account for this equipment.

Contingency plans should be established, with the help of FAO and its regional commissions, so that they can be used during locust invasions, outbreaks, upsurges, and plagues. Such plans should be tested in the field and constantly updated in order to remain relevant and useful.

Public awareness campaigns should be conducted to inform farmers, herders, and locals about the desert locust, what the government is doing, and how communities can play an important role in reporting, including the crowd-sourcing of information. Similarly, government awareness campaigns should be developed for directors and employees to raise the basic level of desert locust knowledge and how to respond during locust emergencies. Reports of locusts that appear in social media channels or that are embellished as fake news will need to be properly managed in order to avoid confusion or panic, especially during locust emergencies.

Innovations and new technologies should be harnessed and adopted for use to further improve survey, control, and reporting. This should be accompanied with substantial and intensive training if any new technology is to be adopted and up scaled successfully for use in desert locust management.

To ensure the sustainability of national locust programs in the future, a mechanism should be established to encourage the young generations to work in desert locust survey and control and to continuously provide them with the necessary training and advancement opportunities. Imaginative ways will need to be identified to attract and motivate talented young people who may not initially be inclined to work under the harsh conditions commonly associated with the national locust program.

Lastly, and perhaps most importantly, all countries affected by the desert locust must work together under the FAO coordination to achieve the common goal of effectively and safely managing desert locust and responding to locust emergencies, therefore protecting food security and livelihoods. Collective action, similar to a desert locust swarm, will be stronger and successful in facing this growing common challenge to human security.

References

Ahmad T (2019) Food security, poor farmers and alternatives—a review. In: 9th National wheat conference held at Agriculture College, University of Sargodha, pp 80–86

Anstey ML, Rogers, Ott SM, Burrows SR, M, Simpson SJ (2009) Serotonin mediates behavioral gregarization underlying swarm formation in desert locusts. Science 323:627–630

Babah MAO, Sword GA (2004) Linking locust gregarization to local resource distribution patterns across a large spatial scale. Environ Entomol 33:1577–1583

Balança G, DeVisscher MN (1997) Impacts on nontarget insects of a new insecticide compound used against the desert locust *Schistocerca gregaria* (Forskal 1775). Arch Environ Contamin Toxicol 32:58–62. https://doi.org/10.1007/s002449900155

Benfekih L, Chara B, Doumandji-Mitiche B (2002) Influence of anthropogenic. In: Impact on the habitats and swarming risks of *Dociostaurus maroccanus* and *Locusta migratoria* (Orthoptera, Acrididae) in the Algerian Sahara and the semiarid zone. J Orthopt Res 11:243–250. https://doi.org/10.1665/1082-6467(2002)011[0243:IOAIOT]2.0.CO;2

Benfekih L, Petit D (2010) The annual cycle of Saharan populations of *Locusta migratoria cinerascens* (Orthoptera: Acrididae: Oedipodinae) in Algeria. Ann Soc Entomol Fr 46:351–358. https://doi.org/10.1080/00379271.2010.10697674

Bouaïchi A (1996) The behavioural and environmental bases of gregarization in the desert locust Schistocerca gregaria (Forskal). Ph.D. thesis, University of Oxford

Brader L, Djibo, Faye FG, Ghaout S, Lazar M, Luzietoso PN (2006) Towards a more effective response to desert locusts and their impacts on food security. In: Livelihoods and poverty. Multilateral evaluation of the 2003–05 desert locust campaign. Food and Agriculture Organisation, Rome

Burnett GF (1951) Field observations on the behaviour of the red locust (Nomadacris Septemfasciata Serville) in the solitary phase. https://www.cabdirect.org/cabdirect/abstract/19510500702. Accessed 12 Mar 2018

Cease A (2012) Locust outbreaks and migration in the Asian steppe: the influence of land management practices and host plant nutrient status. https://search.proquest.com/docview/1012769819/abstract/9493761F6ECC4FBFPQ/1. Accessed 3 Sept 2018

Cease AJ, Hao S, Kang , Elser JJ, Harrison JF (2010) Are color or high rearing density related to migratory polyphenism in the band-winged grasshopper, *Oedaleus asiaticus*? J Insect Physiol 56:926–936. https://doi.org/10.1016/j.jinsphys.2010.05.020

Cease AJ, Elser JJ , Fenichel EP, Hadrich JC, Harrison JF, Robinson BE (2015) Living with locusts. In: Connecting soil nitrogen, locust outbreaks, livelihoods, and livestock markets. Bio Sci 65:551–558. https://doi.org/10.1093/biosci/biv048

Cease AJ, Harrison JF, Hao S, Niren D C, Zhang G Kang L (2017) Nutritional imbalance suppresses migratory phenotypes of the Mongolian locust (*Oedaleus asiaticus*). R Soc Open Sci 4:161039. https://doi.org/10.1098/rsos.161039

Chambers PG, Simpson SJ, Raubenheimer D (1995) Behavioural mechanisms of nutrient balancing in *Locusta migratoria* nymphs. Anim Behav 50:1513–1523. https://doi.org/10.1016/0003-3472(95)80007-7

Chandra S, Williams G (1983) Frequency-dependent selection in the grazing behaviour of the desert locust *Schistocerca gregaria*. Ecol Entomol 8:13–21. https://doi.org/10.1111/j.1365-2311.1983.tb00477.x

Chapman RF (1959) Observations on the flight activity of the red locust. In: *Nomadacris Septemfasciata* (Serville) behaviour 14:300–333. https://doi.org/10.1163/156853959X00126

Chapman RF (1976) A biology of locusts. https://www.cabdirect.org/cabdirect/abstract/19760541473

Chapuis MP, Foucart PC, Blondin L, Leménager N, Benoit L (2017) Genetic and morphological variation in non-polyphenic southern African populations of the desert locust. Afr Entomol 25:13–24. https://doi.org/10.4001/003.025.0013

Charlton E (2020) Formative content world cconomic forum

Chen HH, Kang L (2000) Olfactory responses of two species of grasshoppers to plant odours. Entomol Exp Appl 95:129–134.https://doi.org/10.1046/j.1570-7458.2000.00650.x

Cigliano MM, Braun H, Eades DC, Otte D (2017) Orthoptera species file. Version 5.0/5.0

Cisse S, Ghaout S, Mazih A, Babah Ebbe MAO, Benahi AS, Piou C (2013) Effect of vegetation on density thresholds of adult desert locust gregarization from survey data in Mauritania. Entomol Exp Applic 149:159–165. https://doi.org/10.1111/eea.12121

Cisse S, Ghaout S, Mazih A, Ebbe OB, MA, Piou C, (2015) Estimation of density threshold of gregarization of desert locust hoppers from field sampling in Mauritania. Entomol Exp Appl 156:136–148. https://doi.org/10.1111/eea.12323

Collett M, Despland E, Simpson SJ, Krakauer DC (1998) Spatial scales of desert locust gregarization. Proc Natl Acad Sci USA 95:13052–13055. https://doi.org/10.1073/pnas.95.22.13052

COPR (1982) The locust and grasshopper agricultural manual. Overseas Pest Research, London, p 690

Cressman K (2013) Role of remote sensing in desert locust early warning. J Appl Remote Sens 7:075098. https://doi.org/10.1117/1.JRS.7.075098

Cressman K (2016) Desert locust. Biol Environ. In: Hazards risks disasters, pp 87–105. https://doi.org/10.1016/B978-0-12-394847-2.00006-1

Crooks WT, Cheke RA (2014) Soil moisture assessments for brown locust *Locustana pardalina* breeding potential using synthetic aperture radar. JARS 8:084898. https://doi.org/10.1117/1.JRS.8.084898

Cullen DA, Cease AJ, Latchininsky AV, Ayali A, Berry K, Buhl J (2017) From molecules to management. In: Mechanisms and consequences of locust phase polyphenism, in *Advances in Insect Physiology*, ed Verlinden, H. (Oxford: Elsevier), pp 167–285. https://doi.org/10.1016/bs.aiip.2017.06.002

Cullen DA, Sword GA, Dodgson T, Simpson SJ (2010) Behavioural phase change in the Australian plague locust. In: *Chortoicetes terminifera*, is triggered by tactile stimulation of the antennae. J Insect Physiol 56:937–942. https://doi.org/10.1016/j.jinsphys.2010.04.023

D'Alessandro S, Fall AA, Grey G, Simpkin S, Wane A (2015) Senegal. Washington, DC: Agricultural sector risk assessment. PubMed Abstract|Google Scholar

Dawn (2020) Locust attack threatens food security in Pakistan. 11 May 2020

Despland E (2005) Diet breadth and anti-predator strategies in desert locusts and other orthopterans. Orth 14:227–233. https://doi.org/10.1665/1082-6467(2005)14[227:DBAASI]2.0.CO;2

Despland E, Collett M, Simpson SJ (2000) Small-scale processes in desert locust swarm formation. In: How vegetation patterns influence gregarization. Oikos 88:652–662. https://doi.org/10.1034/j.1600-0706.2000.880322.x

Despland E, Rosenberg J, Simpson SJ (2004) Landscape structure and locust swarming. In: A satellite's eye view. Ecography 27:381–391. https://doi.org/10.1111/j.0906-7590.2004.03779.x

Despland E, Simpso SJ (2000) Small-scale vegetation patterns in the parental environment influence the phase state of hatchlings of the desert locust. Physiol Entomol 25:74–81. https://doi.org/10.1046/j.1365-3032.2000.00166.x

Despland E, Simpson SJ (2005a) Food choices of solitarious and gregarious locusts reflect cryptic and aposematic antipredator strategies. Anim Behav 69:471–479. https://doi.org/10.1016/j.anbehav.2004.04.018

Despland E, Simpson SJ (2005b) Surviving the change to warning colouration. In: density-dependent polyphenism suggests a route for the evolution of aposematism. Chemoecology 15:69–75. https://doi.org/10.1007/s00049-005-0296-6

DPI (2018) Spur-throated locust. Department of primary Industries and regional development. https://www.agric.wa.gov.au/pest-insects/spur-throated-locust?nopaging=1

DPI (2019). Yellow-winged locusts. Department of primary Industries and regional development. https://www.agric.wa.gov.au/pasture-management/yellow-winged-locusts

Draper J (1980) The direction of desert locust migration. J Anim Ecol 49(3):959–974. https://doi.org/10.2307/4238.JSTOR4238

Duranton JF, Monard A, Morales RS (2006) Contribution à l'étude de la bio-écologie de deux locustes péruviens. In: *Schistocerca cf. interrita* Scudder 1899 et *Schistocerca piceifrons peruviana* Lynch
Duranton JF, Monard A, Solano R (2001) Outbreaks of schistocerca interrita (Scudder, 1899) in Northern Peru, Metaleptea
Ellis PE, Ashall C (1957) Field studies on diurnal behaviour, movement and aggregation in the desert locust (*Schistocerca gregaria* Forskål). Anti-Locust Bull 25:4–94
El-Mallakh OS, El-Mallakh RS (1994) Insects of the Qur'an. Am Entomol 40:82–84. https://doi.org/10.1093/ae/40.2.82
Evans CS, Bell EA (1979) Non-protein amino acids of *Acacia* species and their effect on the feeding of the acridids *Anacridium melanorhodon* and *Locusta migratoria*. Phytochemistry 18:1807–1810. https://doi.org/10.1016/0031-9422(79)83057-5
FAO (1996) Rome declaration on world food security and world food summit plan of action. Available online at: http://www.fao.org/DOCREP/003/W3613E/W3613E00.HTM
FAO (2016) Locust control campaign in Northern Laos. http://www.fao.org/laos/news/detail-events/en/c/414367/
FAO (2017) The future of food and agriculture—trends and challenges. Rome
FAO (2009) News article: red locust disaster in Eastern Africa. http://www.fao.org/news/story/en/item/21084/icode/. Accessed 12 Mar 2018
FAO (2020) Southwest Asia desert locust crisis appeal. Rapid response and scaled-up action
FAO–WFP (2020a) Joint FAO-WFP news release 6 November 2020. ROME
FAO (2020b) Five things you should know about an age old pest—desert locust dated 11 May 2020. Retrieved 24 Feb 2021
FAO (2020c) Director General address, desert locust status. Rome
FAO (2020d). Global network against food crises. Resilience www.fao.org Retrieved 24 Feb 2021
Farrow RA (1979) Causes of recent changes in the distribution and abundance of the migratory locust (*Locusta migratoria L.*) in Australia in relation to plagues. CSIRO division of entymology, pp 32–41
Feng GH, Fan SX, Liu QF, Yang YB, Ma LX, Cao GS (1994) The determination capacity for eaten of several species grasshoppers in grassland in outside cage condition. Acta Agrestia Sinica 3:230–235
Fisker EN, Bak J, Niassy A (2007) A simulation model to evaluate control strategies for the grasshopper *Oedaleus senegalensis* in West Africa. Crop Protect 26:592–601. https://doi.org/10.1016/j.cropro.2006.04.026
Gall ML, Overson R, Cease A (2019a) A global review on locusts (Orthoptera: Acrididae) and their interactions with livestock grazing practices. Front Ecol Evol
Graham RI, Deacutis JM, Pulpite T, Ponton F, Simpson SJ, Wilson K (2014) Locusts increase carbohydrate consumption to protect against a fungal biopesticide. J Insect Physiol 69:27–34. https://doi.org/10.1016/j.jinsphys.2014.05.015
Graham RI, Deacutis JM, Simpson SJ, Wilson K (2015) Body condition constrains immune function in field populations of female Australian plague locust *Chortoicetes terminifera*. Parasite Immunol 37:233–241. https://doi.org/10.1111/pim.12179
Gray LJ, Sword GA, Anstey ML, Clissold FJ, Simpson SJ (2009) Behavioural phase polyphenism in the Australian plague locust (*Chortoicetes terminifera*). Biol Lett 5:306–309. https://doi.org/10.1098/rsbl.2008.0764
Guo KUN, HAO SG, Sun OJ, Kang LE (2009) Differential responses to warming and increased precipitation among three contrasting grasshopper species. Glob Change Biol 15:2539–2548.https://doi.org/10.1111/j.1365-2486.2009.01861.x
Guo W, Wang X, Ma Z, Xue L, Han J, Yu D (2011) CSP and takeout genes modulate the switch between attraction and repulsion during behavioral phase change in the migratory locust. PLoS Genet 7:e1001291. https://doi.org/10.1371/journal.pgen.1001291
Haroon WM, Pages C, Vassal JM, Abdalla AM, Luong-Skovmand M, Lecoq M (2011) Laboratory and field investigation of a mixture of *Metarhizium acridum* and Neem seed oil against the

Tree Locust *Anacridium melanorhodon melanorhodon* (Orthoptera: Acrididae). Biocontrol Sci. Technol. 21:353–366. https://doi.org/10.1080/09583157.2010.550678

Harvey AW (1983) *Schistocerca piceifrons* (Walker) (Orthoptera: Acrididae), the swarming locust of tropical America. Bull Entomol Res 73:171–184. https://doi.org/10.1017/S0007485300008786

Haseeb H (2020) The express tribune Pakistan

Hernández-Zul MI, Quijano-Carranza JA, Yáñez-López R, Ocampo-Velázquez RV, Torres-Pacheco I, Guevara-González RG (2013) Dynamic simulation model of central American locust *Schistocerca piceifrons* (Orthoptera: Acrididae). Florida Entomol 96:1274–1283. https://doi.org/10.1653/024.096.0405

Huang T (2020) Which countries are most vulnerable to Locust Swarms? May World Resources Institute

Huang X, McNeill M, Zhang Z (2015) Quantitative analysis of plant consumption and preference by *Oedaleus asiaticus* (Acrididae: Oedipodinae) in changed plant communities consisting of three grass species. Environ Entomol 45:163–170. https://doi.org/10.1093/ee/nvv172

Huang X, Wu H, McNeill MR, Qin X, Ma J, Tu X (2016) Quantitative analysis of diet structure by real-time PCR, reveals different feeding patterns by two dominant grasshopper species. Sci Rep 6:32166. https://doi.org/10.1038/srep32166

Hunter DM (2004) Advances in the control of locusts (Orthoptera: Acrididae) in eastern Australia: from crop protection to preventive control. Austr J Entomol 43:293–303. https://doi.org/10.1111/j.1326-6756.2004.00433.x

Hunter DM, Cosenzo EL (1990) The origin of plagues and recent outbreaks of the South American locust, *Schistocerca cancellata* (Orthoptera: Acrididae) in Argentina. Bull Entomol Res 80:295–300. https://doi.org/10.1017/S0007485300050495

Hunter DM, McCulloch L, Wright DE (1981) Lipid accumulation and migratory flight in the Australian plague locust, *Chortoicetes terminifera* (Walker) (Orthoptera: Acrididae). Bull Entomol Res 71:543–546. https://doi.org/10.1017/S0007485300010051

Hunter DM, Milner RJ, Spurgin PA (2001) Aerial treatment of the Australian plague locust, *Chortoicetes terminifera* (Orthoptera: Acrididae) with *Metarhizium anisopliae* (Deuteromycotina: Hyphomycetes). Bull Entomol Res 91:93–99

Hunter Jones P (1967) Life history of the central American Locust, *Schistocerca sp.* (Orthoptera: Acrididae), in the laboratory. Ann Entomol Soc Am 60:468–477. https://doi.org/10.1093/aesa/60.2.46

International Monetary Fund (IMF) (2020) World economic outlook database October 2020. IMF

Jiang X, Maimaitiming ZL (2003) Nocturnal Migration of Grasshopper (Acrididae: *Oedaleus asiaticus*). Acta Agrest Sin 1:75–77

Jutsum AR, Goldsworthy GJ (1976) Fuels for flight in *Locusta*. J Insect Physiol 22:243–249. https://doi.org/10.1016/0022-1910(76)90032-9

Kang L, Chen X, Zhou Y, Liu B, Zheng W, Li R (2004) The analysis of large-scale gene expression correlated to the phase changes of the migratory locust. Proc Natl Acad Sci USA 101:17611–17615. https://doi.org/10.1073/pnas.0407753101

Kieser M, Thackrah A, Rosenberg J (2010) Changes in the outbreak region of the Brown Locust in Southern Africa. http://gadi.agric.za/articles/Kieser_M/kieser_vol4_2002_locust.php

Latchininsky AV (2013) Locusts and remote sensing: a review. JARS 7:075099. https://doi.org/10.1117/1.JRS.7.075099

Lea A (1958a) Recent outbreaks of the brown locust, *Locustana pardalina* (Walk), with special reference to the influence of rainfall. J Entomol Soc South Afr 21:162–213

Lea A (1958b) The continuing challenge of the brown locust. J Entomol Soc South Afr 21:03–15

Lecoq M (2003) Desert Locust threat to agricultural development and food security and FAO/international role in its control. Arab J Pl Prot 21:188–193

Lecoq M, Chamouine A, Luong-Skovmand MH (2011) Phase-dependent color polyphenism in field populations of red locust nymphs (*Nomadacris septemfasciata* Serv.) in Madagascar. Psyche. https://doi.org/10.1155/2011/105352

Le Gall M, Overson R, Cease A (2019b) A global review on Locusts (Orthoptera: Acrididae) and their interactions with livestock grazing practices. Front Ecol Evol 7:263. https://doi.org/10.3389/fevo.2019.00263

Le Gall M, Tooker JF (2017) Developing ecologically based pest management programs for terrestrial molluscs in field and forage crops. J Pest Sci 90:1–14. https://doi.org/10.1007/s10340-017-0858-8

Li J, Li S, Wang D, Ji R (2014) Changes in the contents of stress resistant substances in *Gomphocerus sibiricus* (Orthoptera: Acrididae) under high temperature stress. Acta Entomol Sin 57:1155–1161

Li S, Huang X, McNeill MR, Liu W, Tu X, Ma J (2019) Dietary stress from plant secondary metabolites contributes to grasshopper (Oedaleus asiaticus) migration or plague by regulating insect insulin-like signaling pathway. Front Physiol 10:531. https://doi.org/10.3389/fphys.2019.00531

Lockwood JA, Showler AT, Latchininsky AV (2001) Can we make locust and grasshopper management sustainable? J Orthoptera Res 10:315–329. https://doi.org/10.1665/1082-6467(2001)010[0315:CWMLAG]2.0.CO;2

Ma C, Liu C, Yang P, Kang L (2009) The complete mitochondrial genomes of two band-winged grasshoppers, *Gastrimargus marmoratus* and *Oedaleus asiaticus*. BMC Genomics 10:156. https://doi.org/10.1186/1471-2164-10-156

Ma C, Yang P, Jiang F, CHAPUIS MP, Shali Y, Sword GA (2012) Mitochondrial genomes reveal the global phylogeography and dispersal routes of the migratory locust. Mol Ecol 21:4344–4358.https://doi.org/10.1111/j.1365-294X.2012.05684.x

Ma Z, Guo W, Guo X, Wang X, Kang L (2011) Modulation of behavioral phase changes of the migratory locust by the catecholamine metabolic pathway. Proc Natl Acad Sci USA 108:3882–3887. https://doi.org/10.1073/pnas.1015098108

Ma Z, Guo X, Lei H, Li T, Hao S, Kang L (2015) Octopamine and tyramine respectively regulate attractive and repulsive behavior in locust phase changes. Sci Rep 5:8036. https://doi.org/10.1038/srep08036

Magor JI, Lecoq M, Hunter DM (2008) Preventive control and Desert Locust plagues. Crop Protect 27:1527–1533. https://doi.org/10.1016/j.cropro.2008.08.006

Maxwell-Darling RC (1936) The outbreak centres of *Schistocerca gregaria*, forsk on the Red Sea coast of the Sudan. Bull Entomol Res 27:37–66. https://doi.org/10.1017/S0007485300058107

Medina HE, Cease A, Trumper E (2017) The resurgence of the South American locust (*Schistocerca cancellata*). Metaleptea 37:17–21

Miller GA, Simpson SJ (2010) 1582301. Isolation from a marching band increases haemocyte density in wild locusts (*Chortoicetes terminifera*). Ecol Entomol 35:236–239. https://doi.org/10.1111/j.1365-2311.2010.01180.x

Mohamed Shaluf I (2007) An overview on disasters. Disaster Prev Manag 16:687–703. https://doi.org/10.1108/09653560710837000

Nevo D (1996) The desert locust, *Schistocerca gregaria*, and its control in the land of Israel and the Near East in antiquity, with some reflections on its appearance in Israel in modern times. Phytoparasitica 24:7–32. https://doi.org/10.1007/BF02981450

Noorka IR, Heslop-Harrison JS (2015) Agriculture and climate change in Southeast Asia and the middle east: Breeding, climate change adaptation, agronomy and water security submitted in handbook of Climate Change Adaptation [110652]. https://doi.org/10.1007/978-3-642-40455-9_74-1, www.springer.com

Noorka IR, Heslop-Harrison JS (2019a) Cross-disciplinary drivers to benefit smallholder farmer communities and to achieve the SDGs by various means. In: Leal Filho W (eds) Handbook of Climate Change Resilience. Springer, Cham. https://doi.org/10.1007/978-3-319-71025-9_40-1, www.springer.com

Noorka IR, Heslop-Harrison JS (2019b) Wheat production technology, a preamble to food security in Pakistan. Crop production technologies for sustainable use and conservation, physiological and molecular approaches. CRC Taylor and Francis/Apple Acedamic Press (AAP), USA. https://www.crcpress.com

Noorka IR (2019) Climate risks and adaptation to crop yield in Pakistan: toward water stress tolerance for food security. In: Leal Filho W, Azul A, Brandli L, Özuyar P, Wall T (eds) Climate Action. Encyclopedia of the UN sustainable development goals. Springer, Cham. https://doi.org/10.1007/978-3-319-71063-1_113-1 www.springer.com

Osimani A, Garofalo C, Aquilanti L, Milanović V, Cardinali F, Taccari M (2017) Transferable antibiotic resistances in marketed edible grasshoppers (*Locusta migratoria migratorioides*). J Food Sci 82:1184–1192. https://doi.org/10.1111/1750-3841.13700

Pedgley D (1981) Desert Locust forecasting manual. COPR, London

Pener (1991) Locust phase polymorphism and its endocrine relations. In: Evans PD (ed) Advances in Insect Physiology. Elsevier, London, pp 1–79. https://doi.org/10.1016/S0065-2806(08)60091-0

Pener MP, Simpson SJ (2009) Locust phase polyphenism: an update. In: Simpson SJ, Pener MP (eds) Advances in insect physiology. Academic Press, London, pp 1–272. https://doi.org/10.1016/S0065-2806(08)36001-9

Phiriyangkul P, Srinroch C, Srisomsap C, Chokchaichamnankit D, Punyarit P (2015) Effect of food thermal processing on allergenicity proteins in Bombay locust (*Patanga succincta*). Int J Food Eng 1:23–28. https://doi.org/10.18178/ijfe.1.1.23-28

Piou C, Lebourgeois V, Benahi AS, Bonnal V, Jaavar MH, Lecoq M (2013) Coupling historical prospection data and a remotely-sensed vegetation index for the preventative control of Desert locusts. Basic Appl Ecol 14:593–604. https://doi.org/10.1016/j.baae.2013.08.007

Poot-Pech MA, Ruiz-Sánchez E, Ballina-Gómez HS, Gamboa-Angulo MM, Reyes-Ramírez A (2016) Olfactory response and host plant feeding of the Central American Locust *Schistocerca piceifrons piceifrons*. In: Walker to common plants in a gregarious zone. Neotrop Entomol 45:382–388. https://doi.org/10.1007/s13744-016-0385-y

Poot-Pech MA, Ruiz-Sánchez E, Gamboa-Angulo M, Ballina-Gómez HS, Reyes-Ramírez A (2018) Population fluctuation of *Schistocerca piceifrons piceifrons* (Orthoptera: Acrididae) in the Yucatán Península and its relation with the environmental conditions. Rev Biol Trop 66:403–414. https://doi.org/10.15517/rbt.v66i1.29502

Popov GB, Duranton JF, Gigault, J (1991) Etude Écologique des Biotopes du Criquet Pèlerin# Schistocerca gregaria (Forskal, 1775) en Afrique Nord-Occidentale. In: Mise en Évidence et Description des Unités Territoriales Écologiquement Homogènes. CIRAD-PRIFAS. Swarm Shift: How Locusts Switch Phases When Numbers Swell

Price RE, Brown HD (2000) A century of locust control in South Africa. In: Workshop on research priorities for migrant pests of agriculture in Southern Africa (Chatham). pp 37–49

Rankin MA, Burchsted JCA (1992) The cost of migration in insects. Annu Rev Entomol 37:533–559. https://doi.org/10.1146/annurev.en.37.010192.002533

Raubenheimer D, Simpson SJ (1993) The geometry of compensatory feeding in the locust. Anim Behav 45:953–964. https://doi.org/10.1006/anbe.1993.1114

Ricciuti Ed (2019) Swarm shift. In: How Locusts Switch Phases When Numbers Swell

Riley JR, Reynolds DR (1983) A long-range migration of grasshoppers observed in the Sahelian zone of Mali by two radars. J Anim Ecol 167–183. https://doi.org/10.2307/4594

Robinson MD (2001) Desert nitrogen cycles. In, fecal nitrogen from a population of the Sahelian Tree Locust in Oman. Sultan Qaboos Univ J Sci 6:33–38.https://doi.org/10.24200/squjs.vol6iss1pp33-38

Roessingh P, Bouaïchi A, Simpson SJ (1998) Effects of sensory stimuli on the behavioural phase state of the desert locust Schistocerca Gregaria. J Insect Physiol 44:883–893. https://doi.org/10.1016/S0022-1910(98)00070-5

Roffey J, Magor JI (2003) Desert Locust popualation dynamics parameters. Technical Series-Desert Locust Field Reserch Stations (FAO)

Roffey J, Popov G (1968) Environmental and behavioural processes in a desert locust outbreak. Nature 219:446. https://doi.org/10.1038/219446a0

Rogers SM, Cullen DA, Anstey M, Burrows M, Despland E, Dodgson T (2014) Rapid behavioural gregarization in the desert locust, *Schistocerca gregaria* entails synchronous changes in both

activity and attraction to conspecifics. J Insect Physiol 65:9–26. https://doi.org/10.1016/j.jinsphys.2014.04.004
Rogers SM, Matheson T, Despland E, Dodgson T, Burrows M, Simpson SJ (2003) Mechanosensory-induced behavioural gregarization in the desert locust *Schistocerca gregaria.* J Exp Biol 206:3991–4002. https://doi.org/10.1242/jeb.00648. SENASICA-D GSV. (2016). *Langosta Centroamericana [Schistocerca piceifrons piceifrons*
Simpson SJ, Raubenheimer D (2000) The hungry locust. Adv Study Behav 29:1–44. https://doi.org/10.1016/S0065-3454(08)60102-3
Simpson SJ, Raubenheimer D, Behmer ST, Whitworth A, Wright GA (2002) A comparison of nutritional regulation in solitarious- and gregarious-phase nymphs of the desert locust Schistocerca gregaria. J Exp Biol 205:121–129
Skaf RM (1972) Problem of introducing modern methods of chemical control of locusts in the developing countries. In: International study conference on the current and future problems of acridology, London
Song H (2011) Density-dependent phase polyphenism in nonmodel locusts IN a minireview. Psyche 2011:741769. https://doi.org/10.1155/2011/741769
Song H, Mariño-Pérez R, Woller DA, Cigliano MM (2018) Evolution, diversification, and biogeography of grasshoppers (Orthoptera: Acrididae). Insect Syst Divers 2:1–25. https://doi.org/10.1093/isd/ixy008
Stanley M (2018) Locusts Swarm in the Pilbara and Kimberley, costing farmers thousands. ABC Rural. Available online https://www.abc.net.au/news/rural/2018-04-02/yellow-winged-locust-plague-swarms-northern-wa-stations/9603136
Steedman A (1990) Locust handbook. Natural Resources Institute, Chatham
Stige LC, Chan KS, Zhang Z, Frank D, Stenseth NC (2007) Thousand-year-long Chinese time series reveals climatic forcing of decadal locust dynamics. Proc Natl Acad Sci USA 104:16188–16193. https://doi.org/10.1073/pnas.0706813104
Stolyarov MV (2000) Strategy and tactics of gregarious locust control. Zashchita Karantin Rastenii 10:17–19
Sword GA (1999) Density-dependent warning coloration. Nature 397:217. https://doi.org/10.1038/16609
Sword GA (2002) A role for phenotypic plasticity in the evolution of aposematism. Proc R Soc Lond B Biol Sci 269:1639–1644. https://doi.org/10.1098/rspb.2002.2060
Sword GA, Simpson, SJ, El Hadi OTM, Wilps H (2000) Density–dependent aposematism in the desert locust. *Proc. R. Soc. Lond. Ser. B Biol. Sci.* 267, pp 63–68.https://doi.org/10.1098/rspb.2000.0967
Symmons P (2009) A critique of Preventive control and desert locust plagues. Crop Protect 28:905–907. https://doi.org/10.1016/j.cropro.2009.04.012
Symmons PM, Cressman K (2001) Desert Locust Guidelines: biology and behavior. Food and Agriculture Organization of the United Nations, Rome
Tanaka S, Zhu DH (2005) Outbreaks of the migratory locust Locusta migratoria (Orthoptera: Acrididae) and control in China. Appl Entomol Zool 40:257–263. https://doi.org/10.1303/aez.2005.257
Thindwa HP (1999) Red Locust population monitoring and control in Malawi, 1988–1998. Int J Trop Insect Sci 19:351–354. https://doi.org/10.1017/S174275840001897X
Tian H, Stige LC, Cazelles B, Kausrud KL, Svarverud R, Stenseth NC (2011) Reconstruction of a 1910-y-long locust series reveals consistent associations with climate fluctuations in China. Proc Natl Acad Sci USA 108:14521–14526. https://doi.org/10.1073/pnas.1100189108
Toleubayev K, Jansen K, van Huis A (2007) Locust control in transition: the loss and reinvention of collective action in post-soviet Kazakhstan. Ecol Soc 12:38. https://doi.org/10.5751/ES-02229-120238
Uvarov B (1966) Grasshoppers and Locusts. In: A handbook of general acridology, Aanatomy, physiology, development, phase polymorphism, introduction to taxonomy. University Press, Cambridge

Uvarov B (1977) Grasshoppers and Locusts. In: A handbook of general acridology Vol 2. Behaviour, ecology, biogeography, population dynamics. Centre for Overseas Pest Research, Cambridge
Uvarov BP (1936) The oriental migratory locust (*Locusta migratoria manilensis*, Meyen 1835). Bull Entomol Res 27:91–104. https://doi.org/10.1017/S0007485300058144
Van Der Werf W, Woldewahid G, Van Huis A, Butrous M, Sykora K (2005) Plant communities can predict the distribution of solitarious desert locust *Schistocerca gregaria*. J Appl Ecol 42:989–997. https://doi.org/10.1111/j.1365-2664.2005.01073.x
Van Huis A, Cressman K, Magor JI (2007) Preventing desert locust plagues: optimizing management interventions. Entomol Exp Applic 122:191–214. https://doi.org/10.1111/j.1570-7458.2006.00517.x
Van Huis A, Woldewahid G, Toleubayev K, Van Der Werf W (2008) Relationships between food quality and fitness in the desert locust, *Schistocerca gregaria*, and its distribution over habitats on the Red Sea coastal plain of Sudan. Entomol Exp Applic 127:144–156
Veran S, Simpson SJ , Sword GA Deveson, E, Piry S, Hines JE (2015) Modeling spatiotemporal dynamics of outbreaking species: influence of environment and migration in a locust. Ecology 96:737–748.https://doi.org/10.1890/14-0183.1
Walker PR, Hill L, Bailey E (1970) Feeding activity, respiration, and lipid and carbohydrate content of the male desert locust during adult development. J Insect Physiol 16:1001–1015. https://doi.org/10.1016/0022-1910(70)90229-5
Waloff Z, Green, SM (1976) Some temporal characteristics of desert locust plagues with a statistical analysis. Antilocust Mem Minist Overseas Dev Antilocust Res Cent Lond 36
Weis-Fogh T (1952) Fat combustion and metabolic rate of flying locusts (*Schistocerca gregaria* Forskaal). Phil Trans R Soc Lond B 237:1–36. https://doi.org/10.1098/rstb.1952.0011
Wilps H, Diop B (1997) Field investigations on *Schistocerca gregaria* (Forskaal) adults, hoppers and hopper bands. In: Krall S, Peveling R, Ba Diallo D (eds) New Strategies in Locust Control. Springer, Basel, pp 117–128. https://doi.org/10.1007/978-3-0348-9202-5_16
Word ML, Hall SJ, Robinson B, Manneh B, Beye A, Cease AJ (2019) Soil-targeted interventions could alleviate locust and grasshopper pest pressure in West Africa. Sci Total Environ 663:632–643. https://doi.org/10.1016/j.scitotenv.2019.01.313
World Bank (2020a) The locust crisis: the World Bank's Response
World Bank (2020b) The locust crisis—the World Bank's response. www.worldbank.org
World Food Programme (2020) Global report on food crises. www.wfp.org retrieved on 24/02/2021
Wright DE (1983) The origin and development of major plagues of Chortoicetes terminifera. Walker, Oxford
Wright DE, Symmons PM (1987) The development and control of the 1984 plague of the Australian plague locust, *Chortoicetes terminifera* (Walker). Crop Protect 6:13–19. https://doi.org/10.1016/0261-2194(87)90022-6
Yang L, Wang J (2004) Meteorological factors on grasshopper bloom in Hami Area. Chin J Ecol 6:009
Zhang L, Hunter D (2017) Management of locusts and grasshoppers in China. J Orthoptera Res 26:155. https://doi.org/10.3897/jor.26.20119
Zhang L, Lecoq M, Latchininsky A, Hunter D (2019) Locust and grasshopper management. Annu Rev Entomol 64:15–34. https://doi.org/10.1146/annurev-ento-011118-112500
Zhang Z, Elser JJ, Cease AJ, Zhang X, Yu Q (2014) Grasshoppers regulate N: P Stoichiometric Homeostasis by changing phosphorus contents in. https://doi.org/10.1371/journal.pone.0103697

Tasneem Ahmad holds a Ph.D. degree in Agricultural Entomology and has more than 30 years of experience in plant protection, phytosanitary measures and pesticides management in Pakistan. He is the former Director General and Adviser, Department of Plant Protection, Government of Pakistan. He served for more than two decades in the National Desert Locust Survey and Control Organization. He led this organization and controlled the desert locust invasions with the help of ground and aerial operations in Pakistan. He was a member of the standard-setting body of IPPC

and ICPM (FAO) during 2010–11. He participated in many international conferences on desert locust: SWAC, APPPC and NEPPO. He has more than 50 publications in his credit, including research articles, conference papers, and newspaper columns.

Keith Cressman is the Senior Locust Forecasting Officer at the Food and Agriculture Organization of the United Nations (FAO). For more than 33 years, he has been providing forecasts and early warning to countries as FAO's top expert. He has established innovative early warning systems for other transboundary pests such as Fall Armyworm and Red Palm Weevil. He began his career with FAO by being posted in Sudan during the last major Desert Locust plague (1987–1989). Prior to FAO, he worked as a Peace Corps volunteer in plant protection in Tunisia (1981–1983) and with USDA/APHIS/ARS on cotton pests in Phoenix, Arizona (1983–1985). He obtained a B.Sc. in Biology from Willamette University in Oregon, USA (1977–1981) and a M.Sc. in International Agriculture Development / Plant Protection from the University of California, Davis (1985–1987). He has published lot several works on desert locust surveillance, remote sensing and control.

Marwa Ben Omrane is an Agricultural Engineer qualified from the National Agronomic Institute of Tunisia (INAT), Tunisia. She holds a Master's degree in Science from the Mediterranean Agronomic Institute of Montpellier, France and a Master's degree in Agricultural Management and Sustainable Development at the University of Montpellier 3, France. She has worked with the ICARDA as a Research Engineer. She also served as an agricultural engineer within the framework of the European project for SOLINAZO, an Innovation within the chamber of agriculture of Indre and the AXEREAL Cooperative in France. She is expert in scientific and technical knowledge of agriculture and environment studies.

Mohammad Katbeh Bader is an International Phytosanitary Expert with nearly 31 years of experience in diverse fields of Plant Wealth, Integrated Pest Management/Safe and Effective use of Pesticides, Seed Potato, Desert Locust, Strategic Planning, and Agricultural Polices and Regulations. He is the Former Chair Person of the International Plant Protection Convention as well as a member in the Standard Committee and Subsidiary Body of Dispute Settlement of IPPC/FAO. Mr. Bader is the Former Secretary General Assistant for Plant Wealth, Ministry of Agriculture, Jordan and Agricultural Legislation Specialist at the Policy and Regulation Sector, Abu-Dhabi Food Control Authority, United Arab Emirates. He holds an M.Sc. in Plant Protection from Jordan University.

The Potential of Edible Wild Fruits as Alternative Option to Ensure Food Security in a Changing Climate: A Case Study from Pakistan

Haleema Sadia, Mushtaq Ahmad, Azaiez Ouled Belgacem, Muhammad Zafar, Mirza Barjees Baig, Shazia Sultana, Salman Majeed, and Ghulam Yaseen

Abstract Climate change and food security are highly interlinked challenges currently faced by human societies. Food and nutrition insecurity has increased due to a greater sensitivity to shifting climatic conditions and obsolete food production and processing methods. To face such challenges, climate-smart agriculture can be referred to as an approach that aims to promote sustainable agriculture and ensure food security. In Pakistan, the extent and direction of climate change impacts on food production have been recorded. This phenomenon has negatively impacted both agriculture and wild edible crops, thus threatening the food security of the country. Nature, on the other hand, has endowed Pakistan with a rich diversity of edible wild fruits (EWFs), which are used by most food-insecure countries. EWFs usually grow in the country's tropical, subtropical, temperate, and alpine forests, plains, and deserts to suitably address the dual intervened issue. This chapter attempts to screen the nutritional and antioxidant potential of four underutilized EWFs of family Rosaceae, with a special emphasis on their mineral diversity, proximate composition, bioactive compounds, free radical scavenging activity using various assays and

H. Sadia · M. Ahmad (✉) · M. Zafar · S. Sultana · S. Majeed · G. Yaseen
Department of Plant Sciences, Quaid-I-Azam University, Islamabad, Pakistan
e-mail: mushtaq@qau.edu.pk; mushtaqflora@hotmail.com

M. Zafar
e-mail: zafar@qau.edu.pk

M. Ahmad
Pakistan Academy of Sciences, Islamabad, Pakistan

A. O. Belgacem
Food and Agriculture Organization (FAO), Riyadh, Kingdom of Saudi Arabia
e-mail: azaiez.ouledbelgacem@fao.org

M. B. Baig
Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riyadh, Saudi Arabia
e-mail: mbbaig@ksu.edu

G. Yaseen
Department of Botany, Science and Technology Division, Township Campus, University of Education, Lahore, Pakistan

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_11

analytical methods to study minerals. The findings show that the Rosaceous WEFs are precious natural source of antioxidant/nutraceuticals as supplementing dietary foods. These fruits are not only a food supplement but also an important part of food and nutritional security, as well as a viable alternative for the long-term survival. A variety of techniques that may be used to analyze and cope with the negative effects of climate change has been presented.

Keywords Food security · Micro-nutrients · Pakistan · Proximate composition · Wild edible fruits

1 Introduction

Traditional knowledge and indigenous evidence indicate that a range of wild edible plant species in Pakistan have played an important role in supplying food and medicine for both humans and animals (Ahmad et al. 2008). The majority of wild edible plants are high in protein, minerals, and vitamins, making them a valuable source of nourishment (Maikhuri et al. 1994). The fruits are high in vital nutrients and are available throughout the year, with substantial overlap at times of severe food and nutrient constraint (Munir et al. 2011). Nonetheless, due to people's cereal-based dietary patterns, cultural beliefs, and attitudes, the fruit usage is now relatively low. As a result, the potential nutritious contribution of wild fruits to people's diets is generally untapped (Fentahun and Hager 2009). In current era of food shortage, there is a need to identify natural wild food resources surrounding indigenous communities (Khan et al. 2015; Ahmad et al. 2018a).

2 Edible Wild Fruits: A Source of Food and Nutrition

Wild fruits have been used since ancient civilizations. To enhance both health and nutrition, most human societies consume a range of locally produced fruits (Ali et al. 2008). In recent trends, the use of wild fruit-producing plants is more common and extensive in rural communities and food-insecure areas than in urban ones. Local inhabitants, especially children, may collect different nuts and berries from their surrounding locales to generate a means of earnings and acquire better nutrition (Murray et al. 2001; Shrestha and Dhillion 2006; Ahmad et al. 2018b). There are hundreds of non-conventional and wild fruit species all around the world, which are known for their edible and dietary value. Mostly fruits have sweet taste and generally do not need cooking like most vegetables and cereals (Khan et al. 2011). Thus, fresh or dried variants of wild fruits are widely consumed in many locations and are also used in the production of commercial food products (Ali et al. 2008). Fruits like olives, dates, grapes, figs, and pomegranates might well be considered a great gift from Allah. Since ancient times, edible wild fruits (EWFs) have played a vital part in people's diets. Traditional fruits are inexpensive yet essential nutrition sources for the poor, particularly in areas where malnutrition is prevalent. Because they do not require maintenance, these fruits grow wild and can be easily harvested from the field (Khan and Ahmad 2015). EWFs are essential for local communities as a source of additional food, a healthy diet, shelter, medicine, fuel, and fodder, as well as assisting in resource management through the preservation of critical natural ecosystems (Munir et al. 2011; Ahmad et al. 2012).

3 EWFs: Combating Food and Health Insecurity

The consumption of EWFs seems more common and widespread in food-insecure areas like deserts or dry lands, where they serve as a buffer food which rescues the lives of countless families at times of hunger and food scarcity. The use of EWFs is an important part of people's survival tactics during stressful times such as war, crop loss, insect assault, and drought. For rural people, forest fruits offer an inexpensive and healthy source of food (Teketay et al. 2010; Neudeck et al. 2012). Unlike other cultivated and commercial fruits, EWFs are highly suited to local marginal terrain and difficult growing conditions, allowing for a long-term food production (Idowu 2009). The commercialization of edible wild plant fruits might meet the growing demand for fruits and associated goods in urban areas while also ensuring that they are accessible to everyone (Sadia et al. 2019).

In order to support worldwide efforts to eliminate hidden hunger and enhance the nutrition of both local and distant customers, increased emphasis has recently been focused on the direct and indirect benefits of wild fruit trees in terms of livelihoods and food security (Mithöfer and Waibel 2003). Although cultivated plants are the focal source of food and income for rural population, they are unable to meet the annual food requirements. Thus, the wild edible plants, including underutilized fruits, substantially contribute great share to annual diets and improve the nutrition of several people in developing countries (Ghorbani et al. 2012).

4 EWFs: Medicinal and Dietary Significance

Several studies have demonstrated that many wild plants have a better nutritional value than conventional vegetables and fruits (Orech et al. 2007; Ahmad et al. 2020). Certain wild fruits, according to research, have a better nutritional value than cultivated fruits. These are high in vitamins, minerals, carbs, proteins, fibers, and bioactive substances and have a superior flavor than their produced counterparts, especially those that have been grown for thousands of years (Trichopoulou 2007). Fruits provide vitamins and minerals that are necessary for maintaining human health. Fatty acids are abundant in wild fruits, making them a significant source of nourishment (Vardavas et al. 2006; Tariq et al. 2020). These foods contain carbohydrates, such as starch and free sugars, as well as proteins, lipids, minerals, ascorbic acid, and antioxidants. Wild fruits and their nutritional derivatives have a great energy potentiality and significant therapeutic worth, according to published research and information gathered from credible sources (Leterme et al. 2006).

5 The Nutritional Value and Dietary Requirements of EWFs

Dietary evaluation is a method of categorizing foods based on their nutritional content in order to make it easier to find healthy meals that can enhance dietary quality (Fatima et al. 2018; Hallström et al. 2019). Many studies reported the nutritional potential of wild edible fruits in different regions of world (Turan et al. 2003; Mahapatra and Panda 2012; Chaudhury et al. 2018; Hazarika and Pongener 2018; Rana et al. 2018; Seal et al. 2018; Sereno et al. 2018; Shin et al. 2018; Vekiari and Ouzounidou 2018). The gathered indigenous wild fruits play an important role in the food and nutritional availability of disadvantaged rural and tribal populations. It has been shown that certain wild fruits have a higher nutritional value than farmed ones (Khan et al. 2015). Fruits, unlike other plant products, such as vegetables, do not require cooking, are eaten raw, and have exquisite tastes (Asfaw and Tadesse 2001; Sundriyal and Sundriyal 2004).

6 The Antioxidant Potential of EWFs

In both normal and pathological cell metabolism, free radicals are generated. Natural antioxidants are being studied extensively for their capacity to protect organisms and cells against oxidative stress, which is regarded to be a contributing factor in aging and degenerative diseases. The activity of 'free radical scavenging enzymes' (superoxide dismutase, catalase, peroxidase, etc.) and antioxidant material content, notably phenolic compounds, carotenoids, tocopherol, and ascorbic acid are significantly linked to the plant antioxidant capacity (Elmastas et al. 2007). Antioxidants such as ascorbic acid, vitamin E, and phenolic substances such as flavonoids found in the wild edible fruit plant counteract oxidizing agents produced as a consequence of metabolic activities in humans. Antioxidants have been shown to have anticancer and cardioprotective effects (Cook et al. 1998; Lako et al. 2007).

In the search for novel antioxidants, many plants have been examined. Some natural antioxidants are now accessible commercially as nutritional supplements (Proteggente et al. 2002). Fruits have long been thought to offer significant health advantages as a result of their nutritional properties, particularly their antioxidant activity against cellular oxidation processes. Fruits' benefits may be due to high levels of various antioxidants. These advantages have sparked studies into the total antioxidant capacity (TAC) of fruits, which will undoubtedly help prevent or reduce illness (Capocasa et al. 2008).

7 The Diversity of EWFs in Pakistan

Poverty, restricted access to nutritious meals, and a lack of understanding about adequate and quality diet are the primary causes of malnutrition (Jan et al. 2011; Kabir and Afzal 2016). This is relevant to all countries, including developed ones. For instance, despite varied food supplies, over 37.5 million people in the USA do not have access to a nutritious diet (Shaheen et al. 2017; Yaseen et al. 2019).

In the context of Pakistan, the vast range of climatic and edaphic conditions has resulted in a rich floral diversity, which gave birth to many biodiversity hotspots. The Pakistani flora comprises approximately 8000 higher plant species, of which about 600 species are medicinally important (Khan et al. 2015). In the country's tropical, subtropical, temperate, and alpine forests, a diverse range of wild-grown food species are underutilized (Sadia et al. 2014). More than 90 distinct kinds of non-conventional and wild fruits have been discovered to have substantial edible potential.

Pakistan is an interesting country in terms of fruit production, since it grows nearly all human-consumable fruits. Minor's fruits are high in soluble dietary fiber, which aids in the removal of cholesterol and lipids from the body, as well as promoting smooth bowel movements and providing relief from constipation. Minor fruits contain many antioxidants, including polyphenolic flavonoids, vitamin C, and anthocyanins. These chemicals aid in the protection of the human body against oxidative stress, illnesses, and malignancies. Minor fruits—such as *Ficus carica* (fig), *Grewia asiatica* (phalsa), *Carica papaya* (papaya), *Syzygium cumini* (jamun), *Psidium guajava* (guava), *Punica granatum* (pomegranate), *Morus alba* (mulberry), *Pyrus communis* (pear), *Prunus domestica* (cherry), *Persea americana* (avocado), *Eriobotrya japonica* (loquat), *Litchi chinensis* (litchi), *Olea europaea* (olive) and *Fragaria ananassa* (strawberry)—contain anthocyanins, which are flavonoid polyphenolic chemicals. Because of their high quantity of vitamins, minerals, micronutrients, pigments, and antioxidants, minor fruits offer health-promoting qualities (Ahmad et al. 2015; Malik et al. 2018a).

8 Traditional Uses of EWFs

The traditional uses of wild plants and their products have been documented more frequently in recent years all across the world. In many areas, oral transmission of traditional wild plant usage between older and younger generations is not always guaranteed (Kargıoğlu et al. 2010; Malik et al. 2018b). The consumption of wild food plants has revived or grown in popularity. They were useful as a nutritional supplement since they included trace elements, vitamins, and minerals. However, the consumption is influenced less by calorie intake and more by the pleasure of obtaining wild resources, reviving traditional activities, and appreciating distinctive characteristics (Pardo-de-Santayana et al. 2007; Rehman et al. 2017). Fruits are an acceptable nutrient supplement for a world that is struggling with the challenge of food scarcity (Valvi and Rathod 2011). Even in modern civilizations, there is a growing interest in wild edible plants, which has resulted in one of many ethnobotanical studies. Despite agricultural civilizations, the habit of eating wild plants has not totally disappeared, with several surveys worldwide reporting on their nutritional value and health advantages (Abbasi et al. 2013; Rashid et al. 2018).

9 EWFs: Family Rosaceae

Rosaceae is a fruit family that includes a wide range of fruit varieties, such as juicy peaches, apples, and strawberries, all of which can contribute to a healthy diet for consumers and act as a paradigm for fruit patterning and development research. The Rosaceae family has about 2500 species in 90 genera, many of which are commercially significant crops that produce edible fleshy fruits (such as apple, apricot, cherry, peach, pear, plum, raspberry, and strawberry), nuts (such as almond), and ornamentals (e.g., rose). However, the economic worth of edible Rosaceae crops' fruits, which supply consumers with distinct contributions to a balanced diet, is the main reason for their relevance (Yamamoto and Terakami 2016; Farinati et al. 2017). As a result of increasing nutritional trends, the products that are appealing in terms of both health-promoting and organoleptic aspects are gaining popularity. These traits are remarkably similar to those seen in the fruits of Rosaceae plants, which are high in essential components including polyphenols and vitamins. Due to their short shelf life, Rosaceae fruits are usually frozen or processed into juices, purees, concentrates, syrups, and jams (Milczarek et al. 2021).

10 Climate-Smart Agriculture and Climate Change

Climate change, global population growth, the need for food security, and the decrease of human labor in agriculture, to mention a few, are prompting academics and policymakers to begin implementing numerous new agricultural approaches (Adamides 2020). The agricultural sector's resistance to climate change is one of the most pressing problems for Pakistan's economic growth, since more than two-thirds of the country's population live in rural regions and rely on agriculture for survival and income (Abid et al. 2016).

Agriculture, climate change, and nutrition are all closely interlinked. Temperature rises, heat waves, and droughts will have an influence on agriculture, with the most severe consequences being lower crop yields and animal output, as well as reductions in fisheries and agroforestry in areas already vulnerable to food insecurity. Climate change will have an impact on food quality (diversity, nutrient density, and safety), as well as food costs, according to compelling data (Fanzo et al. 2018). Climate change impends to intensify prevailing threats to food and livelihood security and is expected to affect all components of food security such as availability, access, and utilization (Scherer and Verburg 2017). Climate change will have an impact on crop yield, perhaps causing food security issues. Climate change is the primary driver of food security in the poor world since it impacts agricultural production, stability, and other food system components such as storage, access, and use (Ali et al. 2017). Therefore, in many countries of the world food and nutritional security have become a major concern under climate change.

Climate-smart agriculture (CSA) is an approach consisting of agricultural strategies which help achieve sustainable agriculture and maintain food security in a context of a changing climate. This approach also helps modernize agricultural systems via the use of digital technology. CSA technologies have the potential to improve the sustainability of agricultural operations, resulting in increased production while decreasing the environmental imprint. In such a perspective, neglected and underutilized but nutrient-rich plant species could help bring transformation in food systems and improve health and nutritional security (Panda and Palita 2021).

The purpose of this chapter was to assess and compare the nutritional, proximate, mineral assessment, antioxidant potential, nutritional, and bioactive characteristics of Rosaceous wild fruit species. The findings will aid in the development of baseline data on the nutritional potential of Rosaceous EWFs growing and will assist to sustain the prospect of their usage as functional ingredient sources in the food sector. Furthermore, this research will determine whether climate-smart agricultural settings are ideal for improving the nutritional and bioactive characteristics of these plants.

11 Methodology

11.1 Collection and Identification of WEFs

Extensive fieldwork was done in both flowering and fruiting seasons (spring, early autumn, and summer) of the study period. A total of four different species of unconventional Rosaceous fruits (WEFs) were selected for this study. During field tours, the collection team was accompanied by local people to recognize the dietary use of each harvested sample. About 1–1.5 kg fresh fruit sample of each species was collected at fully ripened stage. The fresh materials were kept temporarily in plastic bags and transported to the experimental laboratory without any delay. Field photographs in both flowering and fruiting conditions were also taken for the correct identification.

The WEFs collected in field were identified using the Flora of Pakistan and Catalogue of vascular plants of West Pakistan and Kashmir (Stewart et al. 1972). The collected plants were compared with reference specimens in Herbarium of Pakistan (ISL). The botanical names were authenticated from correct botanical name service The Plant List (TPL).[1]

11.2 Processing and Preservation of WEFs for Analysis

Healthy fruits and berries without any damage were sorted and then washed with deionized water to remove dust and other extraneous material. They were given an airing at room temperature and blotted dry till the excess moisture was absorbed. Some of the collected samples were dried well under shade, while the others dried in oven (at 40 °C) to protect them from fungal attack. The completely dried samples were ground to a fine powder and further transferred into the airtight zipped bags. The sealed samples were stored in vacuum desiccators in a dark room until used further for analysis. For the Vitamin C analysis, the weighed fresh were ground with 5% metaphosphoric acid and stored in the freezer for further analysis.

11.3 Analytical Methods

The analytical procedures included: nutrients assessment (minerals quantification and proximate composition); in vitro antioxidant assays (TEAC, FRAP, DPPH, PMR); and determination of active antioxidant compounds (vitamin C and carotenoids). Triplicate subsamples were taken for each analytical procedure.

12 Description of Rosaceous EWFs

The study is confined to nutritional and antioxidant analysis of selected Rosaceous EWFs from Pakistan. Four plant species of EWFs commonly used in Pakistan were selected based on indigenous knowledge prevalent among indigenous communities. The botanical information includes field photograph of each species, synonym, flowering-fruiting time, habit–habitat and localities of collection of each species as summarized in Table 1. The nutritional analysis includes evaluation of mineral content (macro- and microelements), heavy metals and proximate components including water and dry matter (ash, crude fats, crude proteins, carbohydrates and estimated energy available). The antioxidant analysis is confined to three components,

[1] www.theplantlist.org.

Table 1 Botanical information of Rosaceous edible wild fruits

Description	*Fragaria nubicola* (Lindl. Ex Hook. F.) Lacaita	*Rosa moschata* Herrm.	*Rosa webbiana* Wall. Ex Royle	*Rubus anatolicus* (Focke) Hausskn
Synonym	*Fragaria vesca* var. *nubicola* Hook. f.	*Rosa moschata* var. *nepalensis* Lindl.	*Rosa maracandica* Bunge	*Rubus sanctus* Schreb.
Common name	Wild Strawberry	Musk Rose	Thorny Rose	Holy Bramble
Flowering period	April–June	April–May	June–July	March–May
Fruiting time	July–September	June–August	August–October	June–July
Habit and habitat	Herb growing in meadows, forest margins, wooded valleys, and on mountain slopes from 1500 to 3500 m	A shrub of arid areas and dry valleys. It also grows on rocky slopes at 1500–3000 m above sea level	It is a shrub growing in grassy places, scrubs, valleys, near farmlands, and on hilly slopes at elevations of 2000–4500 m	A shrub commonly grows in thickets, valleys, forests and on dry slopes, valleys, forests, and thickets at elevations of 1000–2800 m above sea level
Locality	Utror (Kandol Lake), Swat and Kaghan valley, Mansehra	Kumrat valley, upper Dir and Utror, Swat	Sheringal, Upper Dir and Gabral Valley (Baila), Swat	Kalam, Swat, Dir Khas, Upper Dir, Murree

including free radicals scavenging effects using in vitro antiradical assays. Furthermore, in vitro antiradical assays were based on: 2,2-diphenyl-1-picrylhydrazyl scavenging (DPPH); Trolox equivalent antioxidant capacity (TEAC); ferric reducing antioxidant power (FRAP); and Phosphomolybdenium reduction (PMR) using aqueous, methanol, ethanol, and ethyl acetate extracts. These are vitamin C contents and potential carotenoids in the body of living organisms that may be responsible for nutritional values as well as defense against chronic ailments.

12.1 *Nutritional Composition of* Fragaria nubicola

Minerals Content

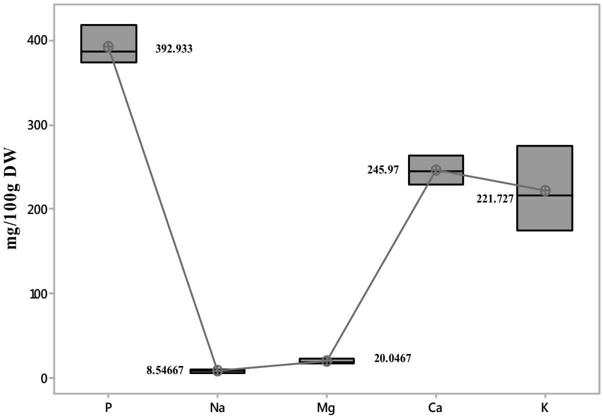
The amounts of inorganic elements (mg/100 DW) in ripened wild strawberries are summarized in Fig. 2a–c. Each box shows the maximum, minimum, and mean values of respective minerals. The concentrations of macro-, micro-minerals, and heavy metals were decreased in orders: P > Ca > K > Mg > Na, Zn > Fe > Mn > Ni > Cu

Fig. 1 Field photograph of *Fragaria nubicola*

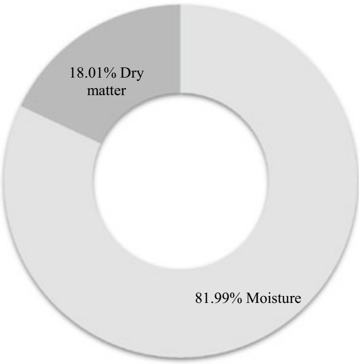
> Co and Pb > Cd > Cr. The results presented noticeable amount of minerals in *F. nubicola* fruits (Fig. 1). The highest content of P (221.72 ± 50.66 mg/100 DW) and Zn (1.4 ± 0.33 mg/100 DW) was recorded among macro- and microelements. Cr was absent in tested fruit sample. In past, Rai et al. (2005) reported that *F. nubicola* is rich in Na and Ca minerals, whereas in the present study Ca was also found in abundant mineral.

Proximate Components

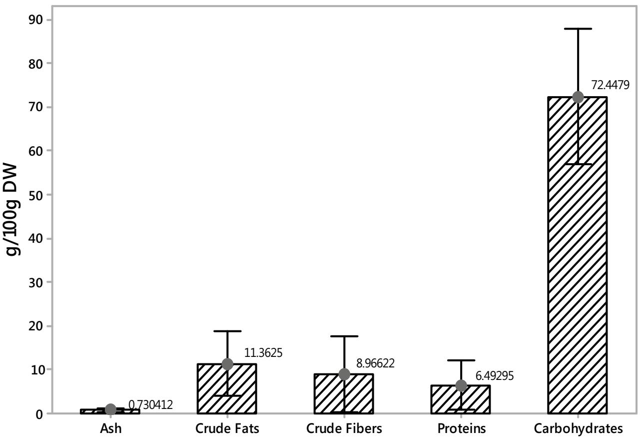
The wild strawberry fruit had high moisture value (81.99 ± 3.17%) and low dry matter content (18 ± 3.17%) (Fig. 2d). The proximate composition on dry weight basis is shown in Fig. 2e. The results show that the fruit was found to be rich in carbohydrates (72.44 ± 6.21%) and crude fats (11.36 ± 2.94%). A considerable amount of crude fibers (6.49 ± 2.23%) and crude proteins (6.49 ± 2.23%) were also present. The percentage ash content was very low (0.73 ± 0.21%). The mean value of energy was 418.02 ± 20.7 kcal/100 g (Fig. 2f). Indrayan et al. (2005) reported that *F. nubicola* had the highest moisture content while fat, protein, carbohydrates are low. On contrary to previous findings, this study reported the lowest amount of moisture and highest content of carbohydrates, indicating *F. nubicola* to be rich in energy-providing compounds.



(a) Macro-minerals concentration (mg/100g DW)

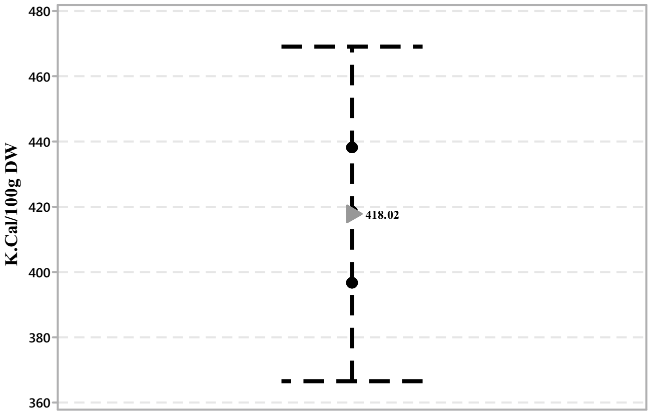


(b) Moisture vs dry matter

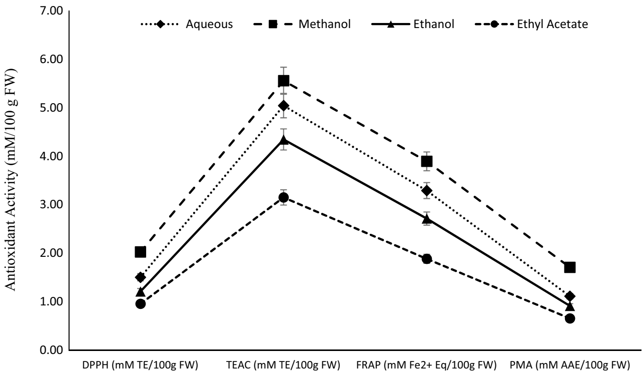


(c) Proximate composition (g/100g DW)

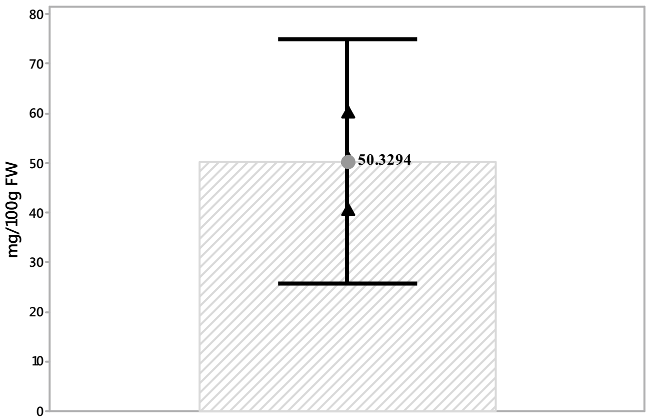
Fig. 2 *Fragaria nubicola*



(d) Energy value (k. cal/100g DW)

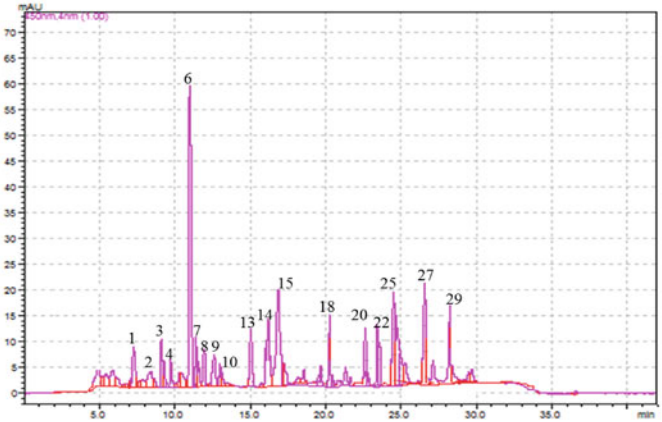


(e) In-vitro antiradical activity



(f) Vitamin-C content

Fig. 2 (continued)



(g) HPLC-PDA chromatogram of carotenoids separated from ethyl acetate extract at 450 nm

Fig. 2 (continued)

12.2 *The Antioxidant Capacity and Potential Constituents of* **Fragaria nubicola**

In Vitro Antiradical Assays

The free radicals scavenging capacity (mM/100 g FW) of four different extracts of wild strawberries is presented in Fig. 2g. Methanolic extract exhibited the highest antioxidant power among all solvent extracts. The descending order of different *F. nubicola* extracts in terms of their activity against different free radical assays was: Methanol > Aqueous > Ethanol > Ethyl acetate. Maximum DPPH inhibition was observed in methanolic extract (2.02 ± 0.01 mM TE/100 g FW) and minimum in ethyl acetate extract (0.953 ± 0.86 mM TE/100 g FW). Similarly, the methanolic extract exhibited the highest FRAP (3.89 ± 0.28 mM $FeSO_4$ Eq/100 g FW), PMA (1.71 ± 0.03 mM AAE/100 g FW), and TEAC (5.56 ± 0.011 mM TE/g100 FW) values; while ethyl acetate fraction possessed the least but noticeable activities by using respective assays (1.88 ± 0.89 mM $FeSO_4$ Eq/100 g FW, 0.65 ± 0.42 mM AAE/100 g FW and 3.15 ± 0.964 mM TE/g100 FW). TEAC values were higher than FRAP, DPPH, and PMA in all respective extracts of wild strawberries. Rakhunde and Ali (2014) revealed that the biochemical investigations of *F. nubicola* showed the significant increase in the catalase and superoxide dismutase enzyme activities, which indicates that *F. nubicola* may decrease the formation of free radicals. It was also indicated that *F. nubicola* reduced the total nitrite and malondialdehyde suggesting that the antioxidant potential of *F. nubicola* may have decreased the formation of oxygen radicals. Anees et al. (2018) reported aqueous phenol content, extract of methanol, and ethyl acetate obtained from *F. nubicola* and their antioxidant potential. The DPPH radical scavenging showed the highest ability against reactive oxygen species in comparison with other standard assays BHT.

Vitamin C Content

The edible wild strawberry had significant amount of vitamin C (50.32 ± 9.88 mg/100 g FW) in fresh fruits (Fig. 2h). The current study's findings are consistent with those of Dai et al. (2012), who found that the vitamin C content was 877.0 and 843.0 mg/kg, respectively. It was reported in previous studies that *F. nubicola* produces some chemical substances like vitamin C which generate a specific physiological action on the human body. Such natural compounds may act as free radical scavenging molecules and help in defense against the production of free radicals (Anees et al. 2018).

Carotenoids Profile

HPLC chromatogram of *F. nubicola* carotenoids extract is shown in Fig. 2i. The prominent carotenoid peaks observed in chromatogram were: all-trans-neochrome, all-trans-violaxanthin, all-trans-lutein, all-trans-zeaxanthin, all-trans-α- and β-cryptoxanthin, 13-cis-zeaxanthin, β-carotene-5, 6-epoxides, all-trans-β-carotene, 13-cis-β-carotene, followed by small peaks of cis-isomers of lutein (Neolutein-A and B), all-trans-neoxanthin, all-trans-mutatoxanthin and all-trans-antheraxanthin. The rare color compounds like all-trans-α, ε, γ-carotenes and their cis-isomers were absent. The total carotenoids content in *F. nubicola* on fresh weight basis was 5.27 ± 0.02 mg/100 g. Strawberry fruits have been shown to contain phenolic such as ellagic acid, ellagic acid glycoside, and coumaryl glycoside, as well as antioxidant, anticancer, anti-inflammatory, and anti-neurodegenerative effects (Hannum 2004; Seeram et al. 2006). The phytochemical research revealed agrimoniin, an anti-tumor and antidiarrheal compound, as the main ellagitannin in *Fragaria vesca* and *Fragaria ananassa* (Vrhovsek et al. 2012).

12.3 *The Nutritional Composition of* Rosa moschata

Minerals Content

The contents of essential and trace elements (mg/100 g DW) in ripened Himalayan musk rose are shown in Fig. 4a–c. Each box shows the maximum, minimum, and mean values of respective minerals. The decreasing orders of macro-, micro-mineral, and heavy metal levels were P > K > Na > Mg > Ca Fe > Cu > Mn > Zn > Ni > Co and Pb > Cr > Cd. The overall analysis of minerals revealed that *R. moschata* fruits (Fig. 3)

Fig. 3 Field photograph of *Rosa moschata*

were relatively rich in P (197.4 ± 18.32 mg/100 g DW) and Fe (7.92 ± 1.85 mg/100 g DW). Cd concentration (0.032 ± 0.012 mg/100 g DW) was observed to be the lowest among all minerals. In some studies conducted on *R. canina*, like Szentmihályi et al. (2002), phosphorus was found to be in high quantity. Fruit mineral composition was influenced not just by species or varieties, but also by the growing environment, including soil and geographical conditions. The available P concentration in soils, which we did not investigate, may influence P absorption by fruit.

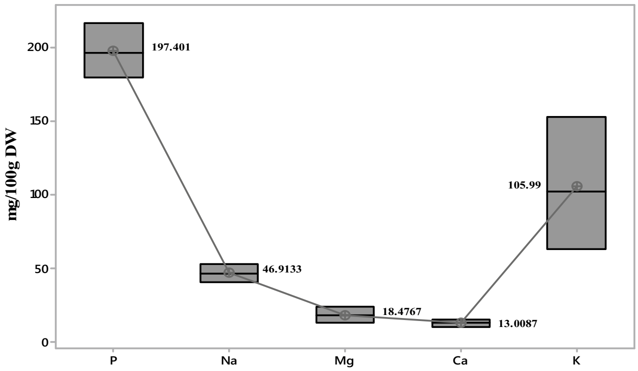
Proximate Components

The Himalayan musk rose fruit had considerably high moisture content (76.36 ± 2.05%) and low dry matter (23.64 ± 2.05%) (Fig. 4d). The proximate composition of shade dried *R. moschata* fruit is presented in Fig. 4e. The percentage values of inorganic ash, crude fats, proteins, and dietary fiber were 5.26 ± 0.28%, 1.11 ± 0.27%, 9.01 ± 4.43%, and 3.88 ± 2.04%, respectively. Rosehip fruits were found to be rich in carbohydrates (80.74 ± 6.12%), and hence a good source of energy too—i.e., 368.96 ± 7.2 kcal/100 g (Fig. 4f). *R. moschata* were evaluated for proximate content. The highest moisture content was found in *R. canina* followed by crude protein, ash percentage, and crude fat (Özcan 2002).

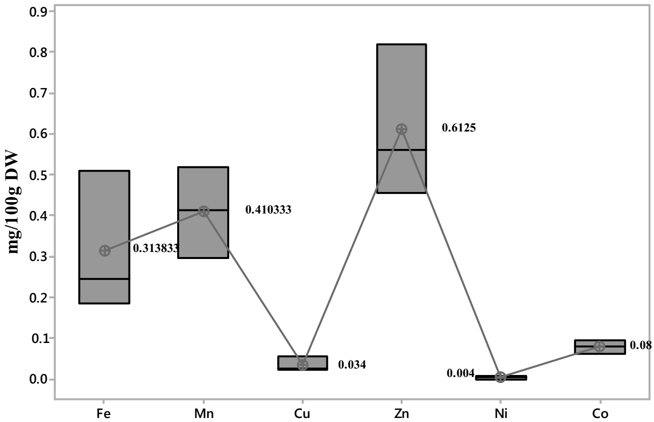
12.4 The Antioxidant Capacity and Potential Constituents of Rosa moschata

In Vitro Antiradical Assays

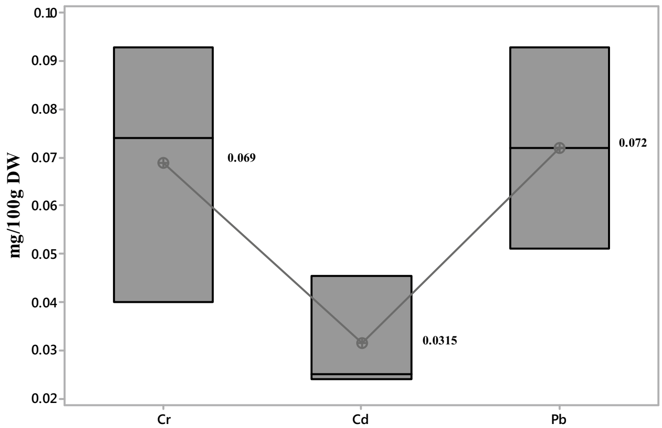
The free radicals scavenging effect (mM/100 g FW) of different extracts (aqueous, methanol, ethanol, ethyl acetate) obtained from *R. moschata* fruit is summarized



(a) Macro-minerals concentration (mg/100g DW)

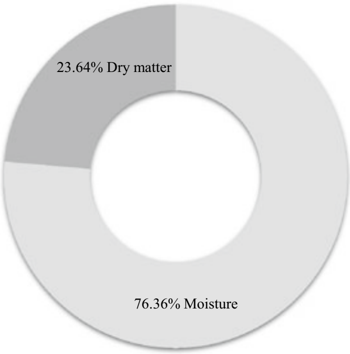


(b) Micro-minerals concentration (mg/100g DW)

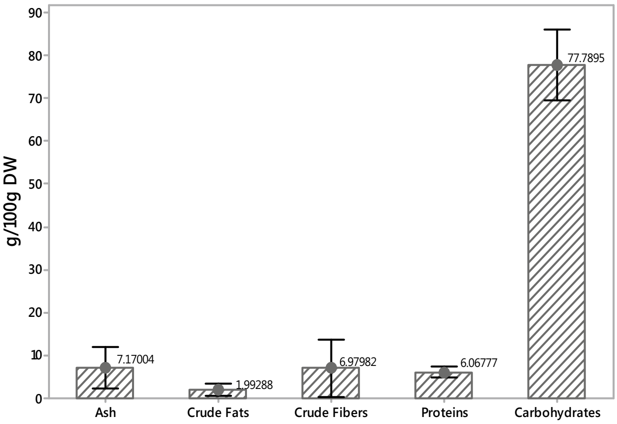


(c) Heavy metals concentration (mg/100g DW)

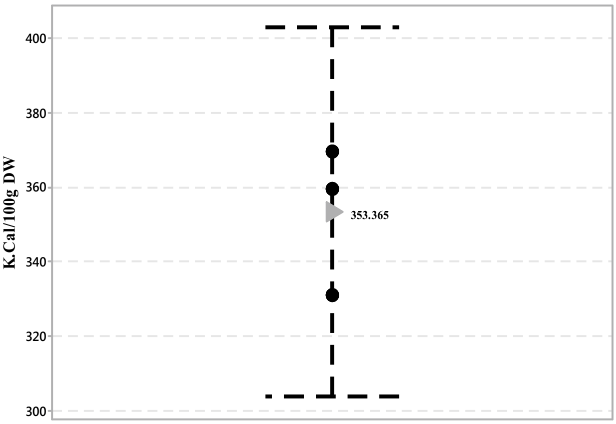
Fig. 4 *Rosa moschata*



(d) Moisture vs dry matter (%)

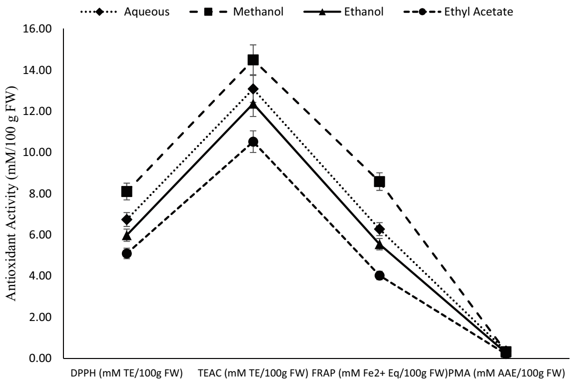


(e) Proximate composition (g/100g DW)

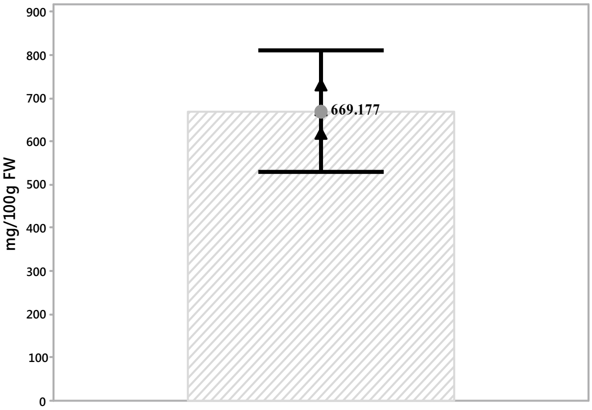


(f) Energy value (k. cal/100g DW)

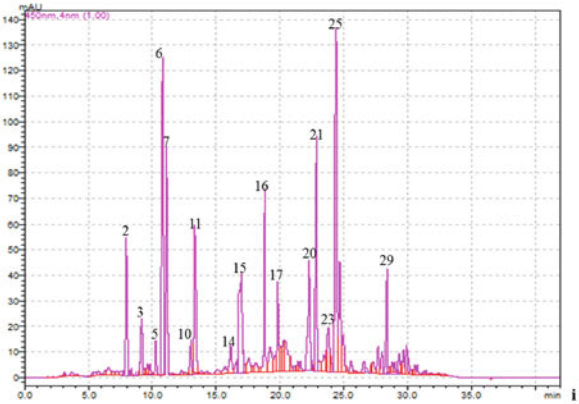
Fig. 4 (continued)



(g) In-vitro antiradical activity



(h) Vitamin-C content



(i) HPLC-PDA chromatogram of carotenoids separated from ethyl acetate extract at 450 nm

Fig. 4 (continued)

in Fig. 4g. Methanolic and aqueous extracts had greater antioxidant ability than ethanolic and ethyl acetate extracts. The descending order of Himalayan musk rose extracts in terms of activity against different free radical assays was: Methanol > Aqueous > Ethanol > Ethyl acetate. DPPH inhibition found to be the highest in methanolic extract (8.103 ± 0.045 mM TE/100 g FW) but the lowest in ethyl acetate extract (5.093 ± 0.81 mM TE/100 g FW). Similar pattern was observed in TEAC, where methanolic and ethyl acetate extracts of investigated fruit sample showed 14.496 ± 0.041 mM TE/100 g FW and 10.52 ± 2.12 mM TE/100 g FW. Methanolic extract also exhibited significantly high FRAP (8.58 ± 0.26 mM $FeSO_4$ Eq/100 g FW) and PMA (0.325 ± 0.12 mM AAE/100 g FW) values as compared to ethyl acetate extracts (4.02 ± 1.74 mM $FeSO_4$ Eq/100 g FW and 0.213 ± 0.12 mM AAE/100 g FW). FRAP values were higher than DPPH, TEAC, and PMA in all respective extracted fraction.

The present study shows the similar findings as mentioned in past studies which support that *R. moschata* has great antioxidant power against many diseases (Shan et al. 2019). Previously, the crude extracts' ferric reducing antioxidant power (FRAP) and Trolox equivalent antioxidant capacity (TEAC) ranged from 983.4 to 2187.1 mol FRAP g^{-1} dry matter and 457.2 to 626.2 mol TEAC g^{-1} dry matter, respectively (Gao et al. 2000). The high phytonutrient content was connected to the high antioxidant capability. Total carotenoids comprised 23.23 mg g^{-1}, while total phenolics were 76.26 mg g^{-1}. The phenolic component was shown to contribute significantly to total antioxidant activities in both trials (overall mean was 90.5 and 75.7%), but ascorbate contributed very marginally (8.6 and 16.9%) and the lipophilic component contributed even less (0.9 and 7.3%). However, when the ratio of antioxidant activity to antioxidant content was compared, the lipophilic component proved to be the most efficient. At a concentration of 250 g ml^{-1}, the crude extracts inhibited lipid peroxidation produced by 2,2′azobis (2,4 dimethylvaleronitrile) (AMVN) by 50.9% and 85.0% in the 2,2′azobis (2amidinopropane) hydrochloride (AAPH) assay. Ascorbate acted as an antioxidant in both peroxyl radical and metal ion-induced lipid peroxidation, but as a pro-oxidant in metal ion-induced lipid peroxidation. The crude extracts exhibited a considerable inhibitory influence on ferric ion-induced lipid peroxidation at a concentration of 25 g ml^{-1} dried rosehip powder, generating 83.7% inhibition.

Vitamin C Content

The total content of ascorbic acid in edible *R. moschata* rose was significantly high. Fresh fruit sample contained 669.17 ± 56.08 mg/100 g of ascorbic acid (Fig. 4h). Previous research in Turkey revealed that the ascorbic acid concentration of *R. canina* ranged from 140 to 1100 mg/100 ml (Misirli et al. 1999; Celik et al. 2009).

Carotenoids Profile

HPLC chromatogram analysis of carotenoids in ethyl acetate extract of *R. moschata* fruit is shown in Fig. 4i. The prominent colored compounds present in *R. moschata* fruit were: all-trans-neoxanthin, all-trans-lutein, all-trans-zeaxanthin, all-trans-canthaxanthin, all-trans-β-cryptoxanthin, β-carotene-5, 6-epoxide, all-trans-ε-carotene, all-trans-rubixanthin, all-trans-lycopene, all-trans-β-carotene and 13-cis-β-carotene. Small amounts of all-trans-violaxanthin, lutein-5, 6-epoxide, neolutein-A, all-trans-α-cryptoxanthin and all-trans-γ-carotene were also present in rosehip fruit. But, peaks for all-trans-neochrome, all-trans-antheraxanthin, all-trans-mutatoxanthin, neolutein-B, cis-zeaxanthin, all-trans-α-carotene and its cis-isomers were not detected. Total carotenoids were estimated as a sum of xanthophylls and carotenes content. So, the estimated value of carotenoid content in *R. moschata* fruit (fresh weight) was 2.43 $\pm$ 0.027 mg/100 g. The carotenoid composition has been investigated in *R. moschata.* Six main carotenoids (β-carotene, lycopene, rubixanthin, gazaniaxanthin, β-cryptoxanthin, and zeaxanthin) as well as minor carotenoids (violaxanthin, antheraxanthin, and β-carotene) have been discovered. The following is an estimate of the typical composition: β-carotene (497.6 mg/kg of dry wt), lycopene (391.9 mg/kg of dry wt), rubixanthin (703.7 mg/kg of dry wt), gazaniaxanthin (289.2 mg/kg of dry wt), β-cryptoxanthin (183.5 mg/kg of dry wt), zeaxanthin (266.6 mg/kg of dry wt), and minor carotenoids (67.1 mg/kg of dry wt) (Hornero-Méndez and Mínguez-Mosquera 2000) (Fig. 5).

Fig. 5 Field photograph and fruiting branch of *Rosa webbiana*

12.5 Nutritional Composition of **Rosa webbiana**

Minerals Content

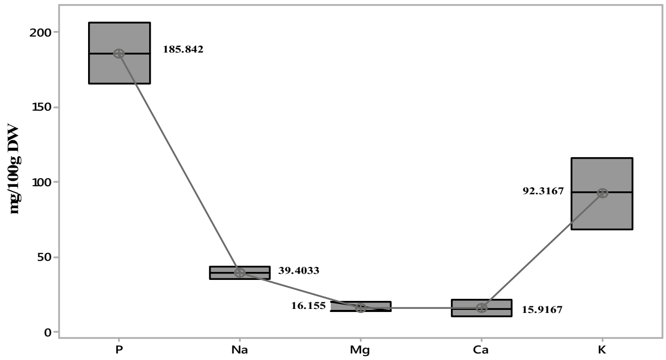
The mineral composition of ripened *R. webbiana* fruit is shown in Fig. 6a–c. The decreasing orders of heavy metal, macro-, and micro-mineral concentrations were: Pb > Cr > Cd, P > K > Na > Mg > Ca, and Fe > Cu > Mn > Zn > Ni > Co. Among the investigated macro- and microelements, thorn rose fruits had significant content of P (197.4 ± 18.32 mg/100 g DW) and Fe (7.92 ± 1.85 mg/100 g DW). Traces of toxic metals were also found—e.g., 0.032 ± 0.01 mg of Pb was recorded in 100 g of shade dried fruit sample. It was reported that *R. canina* are rich in oil, crude protein, potassium, calcium, magnesium, and sodium (Özcan 2002). In another study, Katiyar et al. (2009) found that the fruit of *R. webbiana* was sugar-rich (9.95–35.42%) and mineral matter (0.5–4.7%) including Ca, Fe, and P whose contents show variations from 34–998, 51–671, 2–160, and 3–201 mg/100 g fruit pulp, respectively. This study also coincides with the findings of previous studies confirming that *R. webbiana* is rich in many important minerals including P.

Proximate Components

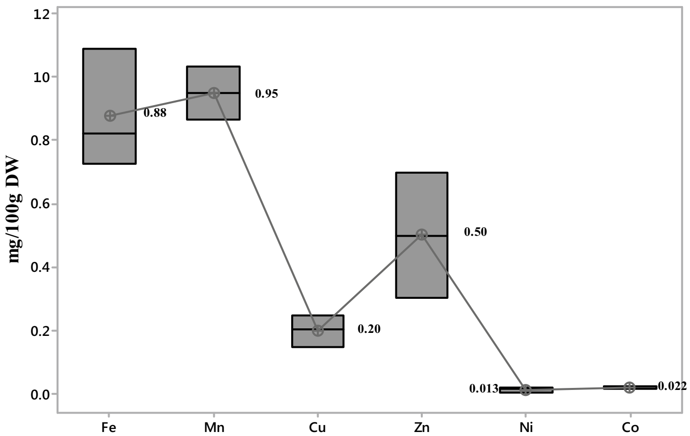
The mean values of moisture and dry matter for thorn rose fruit were: 80.95 ± 5.34% and 19.05 ± 5.34% (Fig. 6d). A clear picture of average proximate composition on dry weight basis is shown in Fig. 6e. According to the results, *R. webbiana* fruit was proximately composed of 5.264 ± 0.28% ash, 1.11 ± 0.27% crude fats, 9.01 ± 4.43% crude proteins, 3.88 ± 2.04% dietary fiber, and 80.73 ± 6.12% total carbohydrates. The mean value of food energy (DW) was 368.96 ± 7.2 Kcal/100 g (Fig. 6f). The proximate analysis and mineral contents of *R. webbiana* fruit were found to be lower in moisture content (50.9%) when compared to flowers (93.7%) and leaves in earlier research (66.4%). Total dry leaf matter (49.1%) was, however, substantially ($p < 0.05$) larger than that of flowers (6.3%) and fruits (33.6%). Fruits had the highest total fat content (1.6%), which was around 300 and 150% higher than flowers and leaves, respectively (Hosni 2011). Mir et al. (2020) found that the proximate content of plants that grow and develop in natural pastures is influenced by the environment, particularly season and climate.

In Vitro Antiradical Assays

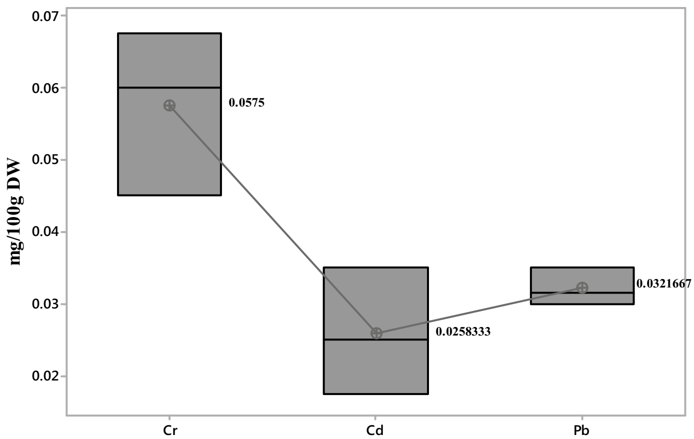
The free radicals scavenging capacity (mM/100 g FW) of *R. webbiana* fruit extracts (aqueous, methanol, ethanol, ethyl acetate) is presented in Fig. 6g. Methanol extract exhibited the highest antioxidant power among all solvent extracts. The descending order of wild rose fruit extracts in terms of ability against different free radical assays was: Methanol > Aqueous > Ethanol > Ethyl acetate. Maximum DPPH inhibition



(a) Macro-minerals concentration (mg/100g DW)

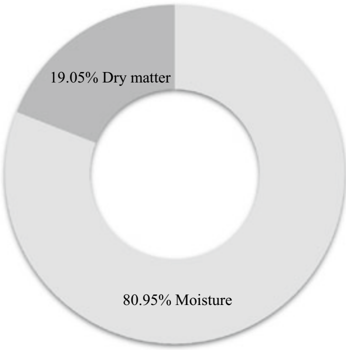


(b) Micro-minerals concentration (mg/100g DW)

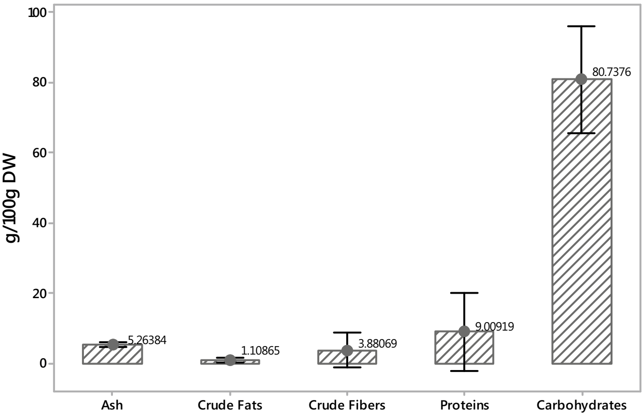


(c) Heavy metals concentration (mg/100g DW)

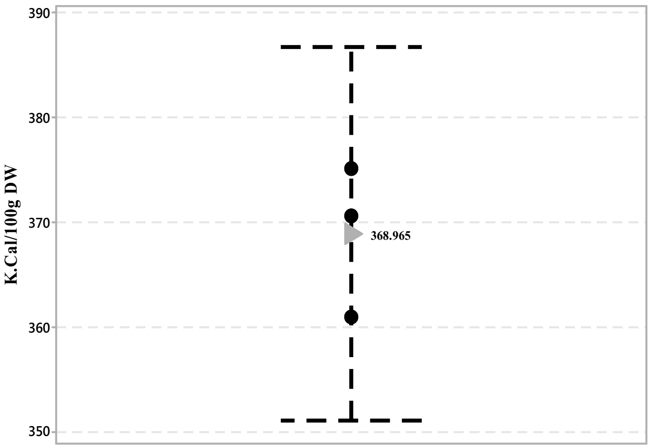
Fig. 6 *Rosa webbiana*



(d) Moisture vs dry matter (%)

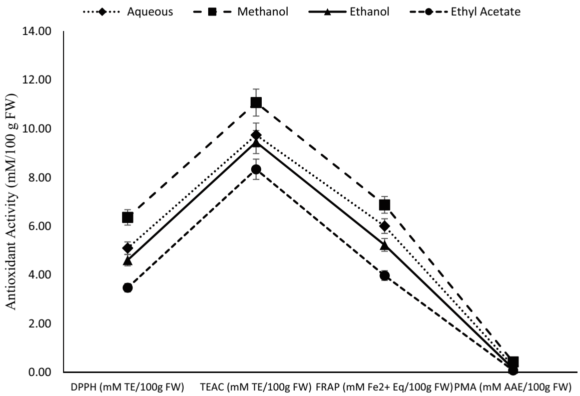


(e) Proximate composition

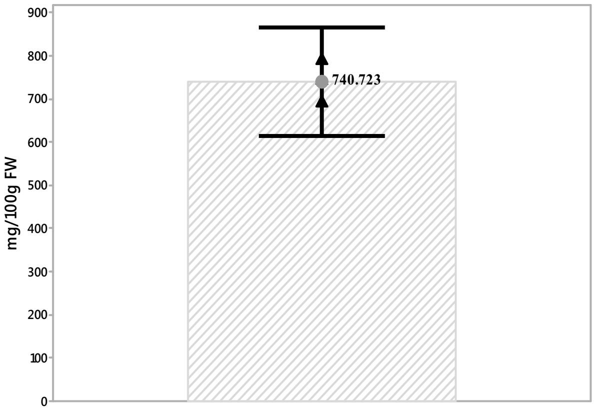


(f) Energy value (k. cal/100g DW)

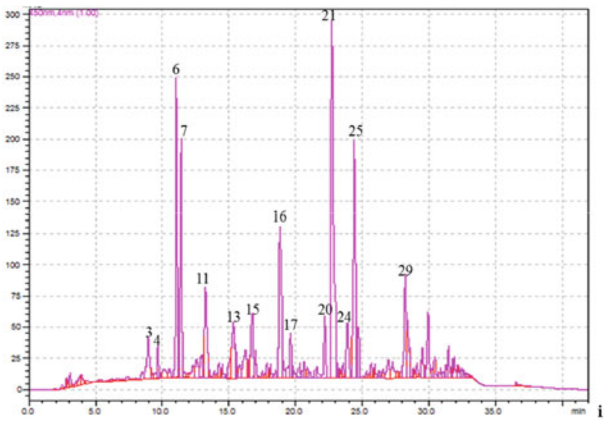
Fig. 6 (continued)



(g) In-vitro antiradical activity



(h) Vitamin-C content



(i) HPLC-PDA chromatogram of carotenoids separated from ethyl acetate extract at 450 nm

Fig. 6 (continued)

was observed in methanol extract (6.36 ± 0.03 mM TE/100 g FW) while minimum in ethyl acetate extract (3.48 ± 2.78 mM TE/100 g FW). Similarly, methanolic wild rose extract exhibited highest FRAP (6.876 ± 0.07 mM $FeSO_4$ Eq/100 g FW), PMA (0.43 ± 0.03 mM AAE/100 g FW), and TEAC (11.07 ± 0.02 mM TE/g100 FW) values while ethyl acetate fraction possessed the lowest but noticeable activity with above three assay (3.97 ± 1.13 mM $FeSO_4$ Eq/100 g FW, 0.083 ± 0.03 mM AAE/100 g FW and 8.34 ± 1.99 mM TE/g100 FW). FRAP values were higher than DPPH, TEAC, and PMA in all respective extracted fractions.

In earlier studies, the scavenging radical activity of the methanolic extract of *R. webbiana* was determined from its DPPH radical quenching ability. The maximum antioxidant activity was discovered in *R. webbiana* fruits, indicating the existence of different active components that may act as natural antioxidants (Roman et al. 2013). Shameh et al. (2018) found that total phenol content, total flavonoid content, and antioxidant activity ranged from 25.13–52.01 mg gallic acid equivalents/g dry weight (DW), 0.61–0.82 mg quercetin equivalents/g DW, 11.47–20.93 mol Fe++/g DW (FRAP), and 31.66–74.44% (DPPH) in another investigation. The most abundant phenolic components in rose petal extracts with antioxidant activity were identified to be p-coumaric acid (647.28 g/g DW) and chlorogenic acid (24.37–135.23 g/g DW).

Vitamin C Content

The analysis revealed that *R. webbiana* fruit was found to be rich in vitamin C and recorded mean value of total ascorbic acid was 740.72 ± 50.32 mg/100 g FW, respectively (Fig. 6h). *R. webbiana* has been found to be high in antioxidants such as polyphenols and ascorbic acid, as well as carotenoids and vitamins B and E, in previous research (Nybom and Werlemark 2017). It indicates that *R. webbiana* is rich natural compounds that are either precursor of vitamin C or work as derivatives of vitamins.

Carotenoids Profile

The carotenoids HPLC chromatogram of *R. webbiana* fruit is given in Fig. 6i, respectively. The major carotenoids found in *R. webbiana* fruit were: all-trans-lutein, all-trans-zeaxanthin, all-trans-canthaxanthin, all-trans-β-cryptoxanthin, all-trans-ε-carotene, β-carotene-5, 6-epoxide, all-trans-lycopene, all-trans-β-carotene, and 13-cis-β-carotene followed by small peaks of all-trans-violaxanthin, all-trans-antheraxanthin, 13-cis-zeaxanthin, all-trans-rubixanthin and all-trans-α-carotene. But cis-isomers of lutein (Neolutein-A and B), lutein-5, 6-epoxide, all-trans-neochrome, all-trans-mutatoxanthin, all-trans-neoxanthin, all-trans-α-cryptoxanthin, and all-trans-γ-carotene were absent in the extracted fruit sample.

The total carotenoids content (including xanthophylls and carotenes) of wild rose fruit was 3.08 ± 0.03 mg/100 g FW. In previous studies, carotenoid composition has been investigated in *R. webbiana*. Six major carotenoids (β-carotene, lycopene, rubixanthin, gazaniaxanthin, β-cryptoxanthin, and zeaxanthin) were identified, as well as minor carotenoids (violaxanthin, antheraxanthin, and γ-zeaxanthin). An average composition has been estimated as follows: β-carotene (497.6 mg/kg of dry wt), lycopene (391.9 mg/kg of dry wt), rubixanthin (703.7 mg/kg of dry wt), gazaniaxanthin (289.2 mg/kg of dry wt), β-cryptoxanthin (183.5 mg/kg of dry wt), zeaxanthin (266.6 mg/kg of dry wt), and minor carotenoids (67.1 mg/kg of dry wt) (Hornero-Méndez and Mínguez-Mosquera 2000).

12.6 Nutritional Composition of Rubus anatolicus

Minerals Content

The concentrations of essential minerals and trace elements in wild blackberry are presented in Fig. 8a–c. The decreasing orders of macro-, micro-minerals, and heavy metal contents were: P > Ca > Mg > K > Na, Fe > Mn > Zn > Cu > Ni > Co, and Cr > Pb > Cd. The results presented appreciable amounts of P (222.47 ± 19.685 mg/100 g DW) and Fe (8.385 ± 1.92 mg/100 g DW) in *R. anatolicus* fruit. The amount of toxic metals was almost negligible; Cd shown the lowest value (0.062 ± 0.02 mg/100 g DW) among all the minerals. In previous study, Livani et al. (2013) reported that there is no significant difference in the amount of sodium, potassium, calcium, and magnesium ions between the mature and immature samples.

Proximate Components

The mean values of moisture and dry matter for wild blackberry fruit were 85.7 ± 5.82% and 14.29 ± 5.82% (Fig. 8d). The average proximate composition on dry weight basis is illustrated in Fig. 8e. The results showed that *R. anatolicus* fruit was proximately composed of 6.26 ± 3.55% ash, 9.883 ± 1.88% crude lipids, 14.18 ± 6.56% crude proteins, 12.301 ± 1.75% dietary fiber, and 57.36 ± 11.85% carbohydrates. The energy provided by 100 g of shade-dried wild blackberries was 375.14 ± 11.85 kcal (Fig. 8f). According to White et al. (2010), the composition of dried cranberry pomace is: moisture (4.5%), protein (2.2%), fat (12%), insoluble fiber (65.5%), soluble fiber (5.7%), other carbohydrates (8.4%), ash (1.1%), and (0.6%) of total polyphenolics.

12.7 *Antioxidant Capacity and Potential Constituents of* Rubus anatolicus

In Vitro Antiradical Assays

The free radicals scavenging capacity (mM/100 g FW) of *R. anatolicus* fruit extracts is summarized in Fig. 8g. Methanolic fruit extract exhibited the highest antioxidant power among all solvent extracts. The descending order of wild blackberries extracts in terms of their activity against different free radical assays was: Methanol > Aqueous > Ethanol > Ethyl acetate. A maximum DPPH inhibition was observed in methanolic extract (2.14 ± 0.01 mM TE/100 g FW) while a minimum in ethyl acetate extract (0.72 ± 0.63 mM TE/100 g FW). Similarly, the methanolic extract exhibited the highest FRAP (0.659 ± 0.04 mM $FeSO_4$ Eq/100 g FW), PMA (0.24 ± 0.03 mM AAE/100 g FW), and TEAC (5.353 ± 0.002 mM TE/g100 FW) values, while ethyl acetate fraction possessed the least but noticeable activity with FRAP, PMR, and TEAC assays (0.16 ± 0.08 mM $FeSO_4$ Eq/100 g FW, 0.052 ± 0.04 mM AAE/100 g FW and 1.401 ± 0.78 mM TE/g100 FW), respectively. TEAC values were higher than DPPH, FRAP, and PMR in all extracted fractions of *R. anatolicus* fruit.

According to Deighton et al. (2000), the antioxidant capacity of the fruit ranged from 0 to 25.3 mol Trolox equivalents g^{-1} (TEAC) or 190 to 66,000 mol II ferric reducing antioxidant power (FRAP). Ascorbic acid had no effect on the antioxidant capacity of *Rubus* juices (10% TEAC). Although there are strong associations between antioxidant capacity (as evaluated by TEAC and FRAP) and total phenols (rxy = 0.6713 and 0.9646, respectively), anthocyanin concentration has a minor impact on antioxidant capacity (rxy = 0.3774, TEAC; rxy = 0.5883, FRAP). The sample with the highest antioxidant capacity (*R. anatolicus*) had the highest phenol content, although anthocyanins only made up a small fraction of the total.

Vitamin C Content

The mean value of total ascorbic acid content in wild blackberry fruit was 23.736 ± 2.12 mg/100 g FW, respectively (Fig. 8h). According to Bernal et al. (2014), *R. glaucus* contains 13.46 and 22.48 g of vitamin C g^{-1} of blackberries. They concluded that the antioxidant and vitamin C content of *R. anatolicus* vary according to the season of collection.

Carotenoids Profile

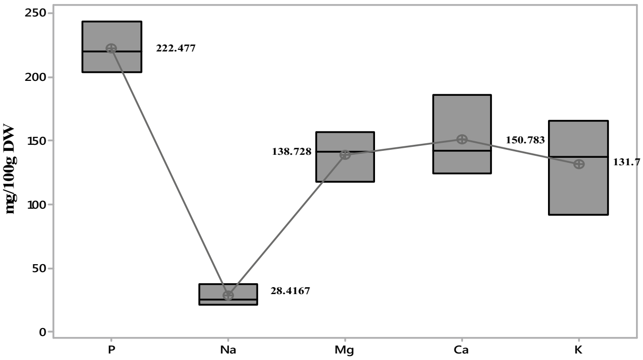
R. anatolicus chromatogram missing of carotenoids from fruit is illustrated below (Fig. 8i), respectively. The main carotenoids recorded in fruit

Fig. 7 Field photograph of Rubus anatolicus

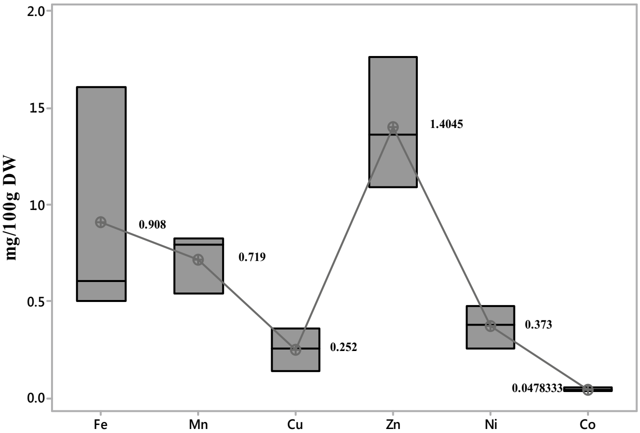
were: all-trans-antheraxanthin, all-trans-lutein, 13-cis-zeaxanthin, all-trans-β-cryptoxanthin, all-trans-rubixanthin, all-trans-lycopene, all-trans-β-carotene, 9-cis-β-carotene followed by small peaks of all-trans-violaxanthin, all-trans-zeaxanthin, all-trans-mutatoxanthin, all-trans-γ-carotene, and 13-cis-β-carotene. Other carotenoid compounds, e.g., c is-isomers of lutein (Neolutein-A and B), lutein-5, 6-epoxide, all-trans-neochrome, all-trans-neoxanthin, all-trans-α-cryptoxanthin, all-trans-ε-carotene, and all-trans-α-carotene, were absent in fruit extract. The total carotenoids content of wild blackberry fruit was 0.69 ± 0.07 mg/100 g FW. Bernal et al. (2014) found that the bilberry had a greater anthocyanin content (1.59 mg of cyn-3-glu g^{-1} vs. 0.26 mg of cyn-3-glu g^{-1} in the blackberry) and total phenols (5.57 mg of caffeic acid g^{-1} bilberry and 2.68 mg caffeic acid g^{-1} blackberry). Sahragard and Jahanbin (2017) extracted an acidic heteropolysaccharide from *R. anatolicus* using water extraction and purification and determined that RAPS-1's total sugar content and specific optical rotation were 96.3% and + 196°, respectively (Fig. 7).

13 Conclusion

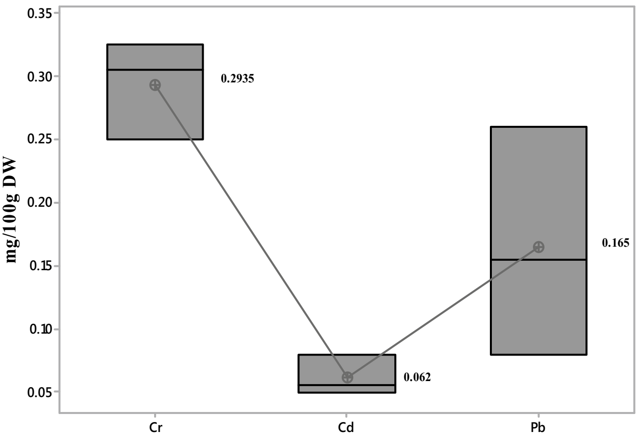
Identifying the potential impact of climate change on wild fruits could reinforce the people' capacity to adapt to changing food security circumstances, particularly in areas that currently rely on edible food species for survival. This chapter emphasized the importance of Rosaceous wild fruit species as a low-cost source of nutrients, as well as their food value in terms of protein, carbohydrate, or vitamin content, in order to establish climate-smart agriculture methods that are related to supply and demand. The Rosaceous EWF study emphasizes the rich nutritional composition of indigenous fruits as well as their potential use as an alternative source of bio-nutrition. This investigation also shows the potential for adopting EWFs as a dietary supplement because it contains key elements such as iron, sodium, potassium, and



(a) Macro-minerals concentration (mg/100g DW)

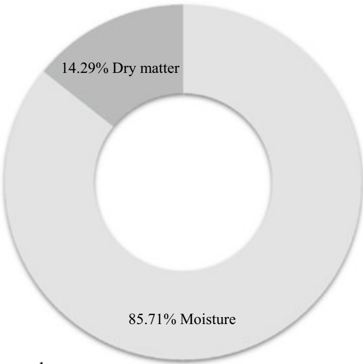


(b) Micro-minerals concentration (mg/100g DW)

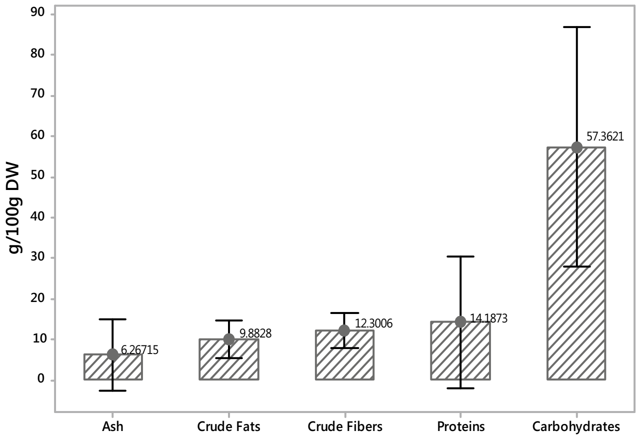


(c) Heavy metals concentration (mg/100g DW)

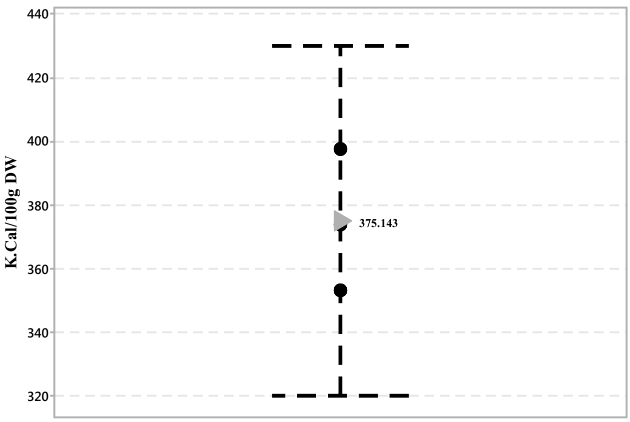
Fig. 8 Rubus anatolicus



(d) Moisture vs dry matter

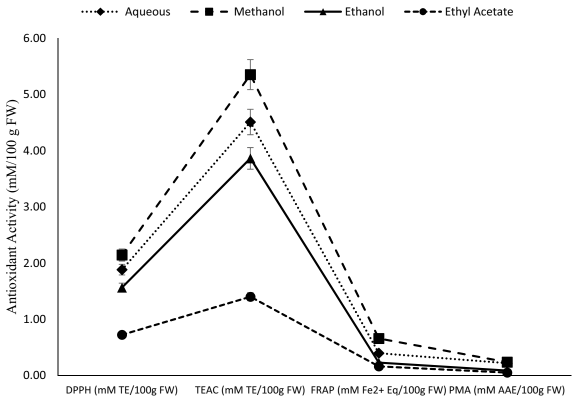


(e) Proximate composition (g/100g DW)

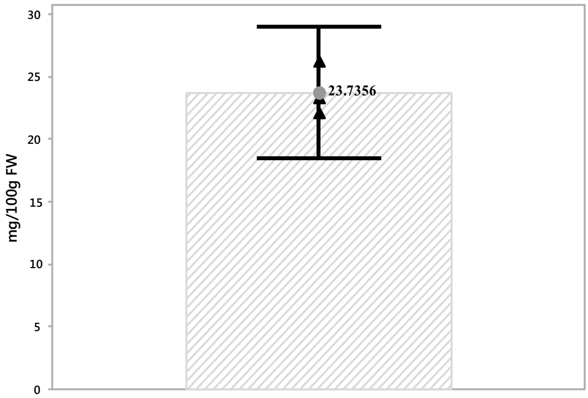


(f) Energy value (k. cal/100g DW)

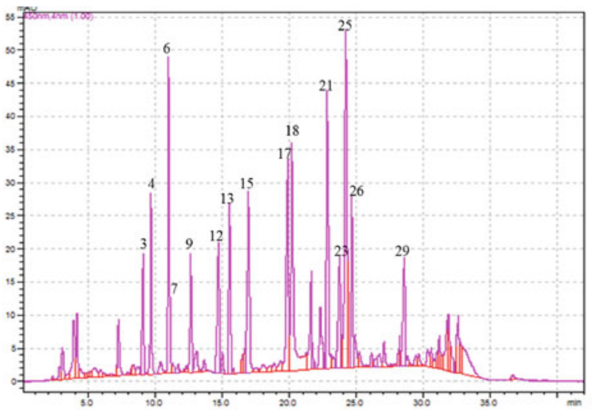
Fig. 8 (continued)



(g) In-vitro antiradical activity



(h) Vitamin-C content



(i) HPLC-PDA chromatogram of carotenoids separated from ethyl acetate extract at 450 nm

Fig. 8 (continued)

calcium. Rosaceae species are also high in nutrients and important minerals, implying that they could be exploited as functional ingredients in the formulation of novel food products. The knowledge of these wild fruit species' antioxidant and nutraceutical potential will be valuable in selecting plants as nutritional supplements as well as developing antioxidant-based medications.

This chapter also contributes to a better understanding of the connections between EWFs, food security, and climate change adaptation.

Acknowledgements We are grateful to Pakistan Academy of Sciences (PAS) for research grant under the project entitled 'Nutraceutical Analysis of Precious Wild Edible Fruits Diversity in Lesser Himalayas of Pakistan.'

References

Abbasi AM, Khan MA, Khan N, Shah MH (2013) Ethnobotanical survey of medicinally important wild edible fruits species used by tribal communities of Lesser Himalayas-Pakistan. J Ethnopharmacol 148(2):528–536

Abid M, Schneider UA, Scheffran J (2016) Adaptation to climate change and its impacts on food productivity and crop income: perspectives of farmers in rural Pakistan. J Rural Stud 47:254–266

Adamides G (2020) A review of climate-smart agriculture applications in Cyprus. Atmosphere 11(9):898

Ahmad M, Khan MA, Zafar M (2008) Traditional herbal cosmetics used by local women communities in district Attock of Northern Pakistan. Indian J Tradit Knowl 7(3):421–424

Ahmad M, Zafar M, Khan MA, Sultana S, Shah GM, Jan G (2012) Ethnomedicinal investigation of phytomedicines among the local communities of arid areas of Pakistan. Indian J Tradit Knowl 11(3):436–446

Ahmad M, Masood S, Sultana S, Hadda TB, Bader A, Zafar M (2015) Antioxidant and nutraceutical value of wild medicinal Rubus berries. Pak J Pharm Sci 28(1):241–247

Ahmad M, Butt MA, Zhang G, Sultana S, Tariq A, Zafar M (2018a) Bergenia ciliata: a comprehensive review of its traditional uses, phytochemistry, pharmacology and safety. Biomed Pharmacother 97:708–721

Ahmad M, Malik K, Tariq A, Zhang G, Yaseen G, Rashid N, Sultana S, Zafar M, Ullah K, Khan MPZ (2018b) Botany, ethnomedicines, phytochemistry and pharmacology of Himalayan Paeony (*Paeonia emodi* Royle.). J Ethnopharmacol 220:197–219

Ahmad S, Zafar M, Shinwari S, Ahmad M, Shinwari ZK, Sultana S, Butt MA (2020) Ethnomedicinal plants and traditional knowledge linked to primary health care among the indigenous communities living in western hilly slopes of Dera Ghazi Khan, Pakistan. Pak J Bot 52(2):519–530

Ali SS, Kasoju N, Luthra A, Singh A, Sharanabasava H, Sahu A, Bora U (2008) Indian medicinal herbs as sources of antioxidants. Food Res Int 41(1):1–15

Ali S, Liu Y, Ishaq M, Shah T, Ilyas A, Din IU (2017) Climate change and its impact on the yield of major food crops: evidence from Pakistan. Foods 6(6):39

Anees S, Dar KB, Bhat AH, Showkat Ahmad S, Hamid R (2018) Anti-hyperlipidemic and antioxidant capacity of active extracts of Fragaria nubicola in high fat diet fed hyperlipidemic rats. Int J Pharm Sci Res 9(6):2228–2237

Asfaw Z, Tadesse M (2001) Prospects for sustainable use and development of wild food plants in Ethiopia. Econ Bot 55(1):47–62

Bernal LJ, Melo LA, Díaz Moreno C (2014) Evaluation of the antioxidant properties and aromatic profile during maturation of the blackberry (Rubus glaucus Benth) and the bilberry (Vaccinium meridionale Swartz). Revista Facultad Nacional De Agronomía Medellín 67(1):7209–7218

Capocasa F, Scalzo J, Mezzetti B, Battino M (2008) Combining quality and antioxidant attributes in the strawberry: the role of genotype. Food Chem 111(4):872–878

Celik F, Kazankaya A, Ercisli S (2009) Fruit characteristics of some selected promising rose hip (Rosa spp.) genotypes from Van region of Turkey. Afr J Agric Res 4(3):236–240

Chaudhury S, Rahaman CH, Singh H, Chaudhuri K, Pillai B, Seal T (2018) Dioscorea alata: a potent wild edible plant consumed by the Lodha Tribal community of West Bengal, India. J Pharmacognosy Phytochem 7:654–663

Cook JA, VanderJagt DJ, Dasgupta A, Mounkaila G, Glew RS, Blackwell W, Glew RH (1998) Use of the Trolox assay to estimate the antioxidant content of seventeen edible wild plants of Niger. Life Sci 63(2):105–110

Dai HP, Lei JJ, Wang C, Fan W (2012) Study on the fertility and fruit quality of natural pentaploid strawberries native to China. In: VII international strawberry symposium 1049, pp 281–287

Deighton N, Brennan R, Finn C, Davies HV (2000) Antioxidant properties of domesticated and wild Rubus species. J Sci Food Agric 80(9):1307–1313

Elmastas M, Isildak O, Turkekul I, Temur N (2007) Determination of antioxidant activity and antioxidant compounds in wild edible mushrooms. J Food Compos Anal 20(3–4):337–345

Fanzo J, Davis C, McLaren R, Choufani J (2018) The effect of climate change across food systems: implications for nutrition outcomes. Glob Food Sec 18:12–19

Farinati S, Rasori A, Varotto S, Bonghi C (2017) Rosaceae fruit development, ripening and post-harvest: an epigenetic perspective. Front Plant Sci 8:1247

Fatima A, Ahmad M, Zafar M, Yaseen G, Khan MPZ, Butt MA, Sultana S (2018) Ethnopharmacological relevance of medicinal plants used for the treatment of oral diseases in Central Punjab-Pakistan. J Herbal Med 12:88–110

Fentahun MT, Hager H (2009) Exploiting locally available resources for food and nutritional security enhancement: wild fruits diversity, potential and state of exploitation in the Amhara region of Ethiopia. Food Secur 1(2):207–219

Gao X, Ohlander M, Jeppsson N, Björk L, Trajkovski V (2000) Changes in antioxidant effects and their relationship to phytonutrients in fruits of sea buckthorn (Hippophae rhamnoides L.) during maturation. J Agric Food Chem 48(5):1485–1490

Ghorbani A, Langenberger G, Sauerborn J (2012) A comparison of the wild food plant use knowledge of ethnic minorities in Naban River Watershed National Nature Reserve, Yunnan, SW China. J Ethnobiol Ethnomed 8(1):1–10

Hallström E, Bergman K, Mifflin K, Parker R, Tyedmers P, Troell M, Ziegler F (2019) Combined climate and nutritional performance of seafoods. J Clean Prod 230:402–411

Hannum SM (2004) Potential impact of strawberries on human health: a review of the science. Crit Rev Food Sci Nutr 44(1):1–17

Hazarika TK, Pongener M (2018) Potential wild edible fruits of Nagaland, North-East India and its significance in the livelihood and nutritional security of rural, indigenous people. Genet Resour Crop Evol 65(1):199–215

Hornero-Méndez D, Mínguez-Mosquera MI (2000) Carotenoid pigments in Rosa mosqueta hips, an alternative carotenoid source for foods. J Agric Food Chem 48(3):825–828

Hosni K (2011) Rosa× alba: source of essential minerals and volatile oils. Nat Prod Bioprospecting 1(1):57–61

Idowu AA (2009) Potential and opportunities for sustainable production and utilisation of horticultural crops in Nigeria. In: 9th African Crop Science, conference proceedings, Cape Town, South Africa, 28 Sept–2 Oct 2009. African Crop Science Society, pp 201–204

Indrayan AK, Sharma S, Durgapal D, Kumar N, Kumar M (2005) Determination of nutritive value and analysis of mineral elements for some medicinally valued plants from Uttaranchal. Curr Sci 1252–1255

Jan G, Khan MA, Ullah F, Jan FG, Ahmad M, Jan M, Zafar M (2011) Ethnobotanical studies on some useful plants of Dir Kohistan valleys, KPK, Pakistan. Pak J Bot 43(4):1849–1852

Kabir M, Afzal MS (2016) Epidemiology of polio virus infection in Pakistan and possible risk factors for its transmission. Asian Pac J Trop Med 9(11):1044–1047

Kargıoğlu M, Cenkci S, Serteser A, Konuk M, Vural G (2010) Traditional uses of wild plants in the middle Aegean region of Turkey. Hum Ecol 38(3):429–450

Katiyar PN, Singh JP, Singh PC (2009) Effect of nutrients and plant growth regulators on physico-chemical parameters and yield of guava (Psidium guajava L.) fruit cv. Allahabad Safeda. Int J Agric Sci 5(1):173–174

Khan MPZ, Ahmad M (2015) Traditional preference of Wild Edible Fruits (WEFs) for digestive disorders (DDs) among the indigenous communities of Swat Valley-Pakistan. J Ethnopharmacol 174:339–354

Khan KY, Khan MA, Ahmad M, Shah GM, Zafar M, Niamat R, Munir M, Abbasi AM, Fazal H, Mazari P, Seema N (2011) Foliar epidermal anatomy of some ethnobotanically important species of genus Ficus Linn. J Med Plants Res 5(9):1627–1638

Khan MPZ, Ahmad M, Zafar M, Sultana S, Ali MI, Sun H (2015) Ethnomedicinal uses of edible wild fruits (EWFs) in Swat Valley, Northern Pakistan. J Ethnopharmacol 173:191–203

Lako J, Trenerry VC, Wahlqvist M, Wattanapenpaiboon N, Sotheeswaran S, Premier R (2007) Phytochemical flavonols, carotenoids and the antioxidant properties of a wide selection of Fijian fruit, vegetables and other readily available foods. Food Chem 101(4):1727–1741

Leterme P, Buldgen A, Estrada F, Londoño AM (2006) Mineral content of tropical fruits and unconventional foods of the Andes and the rain forest of Colombia. Food Chem 95:644–652

Livani F, Ghorbanli M, Sateei A (2013) Effect of maturity on soluble sugars and some ions in Elm-leaved blackberry (Rubus Anatolicus (Focke) Focke Ex Hausskn.) fruit. J Plant Environ Physiol 8:51–58

Mahapatra AK, Panda PC (2012) Wild edible fruit diversity and its significance in the livelihood of indigenous tribals: evidence from eastern India. Food Secur 4(2):219–234

Maikhuri RK, Semwal RL, Singh A, Nautiyal MC (1994) Wild fruits as a contribution to sustainable rural development: a case study from the Garhwal Himalaya. Int J Sustain Dev World Ecol 1(1):56–68

Malik K, Ahmad M, Zhang G, Rashid N, Zafar M, Sultana S, Shah SN (2018a) Traditional plant-based medicines used to treat musculoskeletal disorders in Northern Pakistan. Eur J Integr Med 19:17–64

Malik K, Ahmad M, Bussmann RW, Tariq A, Ullah R, Ali S, Alghtani, Shahat AA, Rashid N, Zafar M, Sultana S, Shah SN (2018b) Ethnobotany of anti-hypertensive plants used in northern Pakistan. Front Pharmacol 09:1–18

Milczarek A, Sójka M, Klewicki R (2021) Transfer of ellagitannins to unclarified juices and purees in the processing of selected fruits of the Rosaceae family. Food Chem 344:128684

Mir SH, Ahmed HA, Ganai AM, Beigh YA (2020) Seasonal variability of palatability and nutrient intake in different age groups of range sheep. Biol Rhythm Res 51(7):1006–1017

Misirli A, Güneri M, Gülcan R (1999) Phenological and pomological properties of rose hip grown in Izmir-Kemalpasa. In: Proceedings of 3rd national horticulture congress, 14–17

Mithöfer D, Waibel H (2003) Income and labour productivity of collection and use of indigenous fruit tree products in Zimbabwe. Agrofor Syst 59(3):295–305

Munir M, Khan MA, Ahmad M, Bano A, Ahmed SN, Tariq K, Tabassum S, Mukhtar T, Ambreen M, Bashir S (2011) Foliar epidermal anatomy of some ethnobotanically important species of wild edible fruits of northern Pakistan. J Med Plants Res 5(24):5873–5880

Murray SS, Schoeninger MJ, Bunn HT, Pickering TR, Marlett JA (2001) Nutritional composition of some wild plant foods and honey used by Hadza foragers of Tanzania. J Food Compos Anal 14(1):3–13

Neudeck L, Avelino L, Bareetseng P, Ngwenya BN, Motsholapheko M (2012) The contribution of edible wild plants to food security, dietary diversity and income of households in Shorobe Village, northern Botswana. Ethnobot Res Appl 10:449–462

Nybom H, Werlemark G (2017) Realizing the potential of health-promoting rosehips from dogroses (Rosa sect. Caninae). Curr Bioact Compd 13(1):3–17
Orech FO, Aagaard-Hansen J, Friis H (2007) Ethnoecology of traditional leafy vegetables of the Luo people of Bondo district, western Kenya. Int J Food Sci Nutr 58(7):522–530
Özcan M (2002) Nutrient composition of rose (Rosa canina L.) seed and oils. J Med Food 5(3):137–140
Panda D, Palita SK (2021) Potential of underutilized wild crops in Koraput, Odisha, India for improving nutritional security and promoting climate resilience. Curr Sci (00113891) 120(6)
Pardo-de-Santayana M, Tardío J, Blanco E, Carvalho AM, Lastra JJ, San Miguel E, Morales R (2007) Traditional knowledge of wild edible plants used in the northwest of the Iberian Peninsula (Spain and Portugal): a comparative study. J Ethnobiol Ethnomed 3(1):1–11
Proteggente AR, Pannala AS, Paganga G, Buren LV, Wagner E, Wiseman S, Rice-Evans CA (2002) The antioxidant activity of regularly consumed fruit and vegetables reflects their phenolic and vitamin C composition. Free Radical Res 36(2):217–233
Rai AK, Sharma RM, Tamang JP (2005) Food value of common edible wild plants of Sikkim. J Hill Res 18:99–103
Rakhunde PB, Ali SA (2014) Antioxidant and cytoprotective effect of Fragaria nubicola on ischemia reperfusion induced brain injury. Ann Exp Biol 2(4):33–38
Rana YS, Tiwari OP, Krishan R, Sharma CM (2018) Determination of nutritional potential of five important wild edible fruits traditionally used in Western Himalaya. Int J Life Sci 6(1):79–86
Rashid N, Gbedomon RC, Ahmad M, Salako VK, Zafar M, Malik K (2018) Traditional knowledge on herbal drinks among indigenous communities in Azad Jammu and Kashmir, Pakistan. J Ethnobiol Ethnomed 14(1):16–36
Rehman MN, Ahmad M, Sultana S, Zafar M, Edwards S (2017) Relative popularity level of medicinal plants in Talagang, Punjab Province, Pakistan. Revista Brasileria De Farmacognosia 27(6):751–775
Roman I, Stănilă A, Stănilă S (2013) Bioactive compounds and antioxidant activity of Rosa canina L. biotypes from spontaneous flora of Transylvania. Chem Cent J 7(1):1–10
Sadia H, Ahmad M, Sultana S, Abdullah AZ, Teong LK, Zafar M, Bano A (2014) Nutrient and mineral assessment of edible wild fig and mulberry fruits. Fruits 69(2):159–166
Sadia H, Zafar M, Ahmad M, Lubna, Khan MPZ, Yaseen G, Ali MI, Sultana S, Kilic O, Zeynep S, Alam N (2019) Foliar epidermal anatomy of some selected wild edible fruits of Pakistan using light microscopy and scanning electron microscopy. Microsc Res Tech 83(3):259–267
Sahragard N, Jahanbin K (2017) Structural elucidation of the main water-soluble polysaccharide from Rubus anatolicus roots. Carbohyd Polym 175:610–617
Scherer L, Verburg PH (2017) Mapping and linking supply-and demand-side measures in climate-smart agriculture. A review. Agron Sustain Dev 37(6):1–17
Seal T, Chaudhuri K, Pillai B (2018) A rapid high-performance liquid chromatography method for the simultaneous estimation of water-soluble vitamin in ten wild edible plants consumed by the tribal people of North-eastern region in India. Pharmacogn Mag 14(55):72
Seeram NP, Zhang Y, Reed JD, Krueger CG, Vaya J (2006) Pomegranate phytochemicals. In: Pomegranates. CRC Press, Boca Raton, pp 21–48
Sereno AB, Bampi M, dos Santos IE, Ferreira SMR, Bertin RL, Krüger CCH (2018) Mineral profile, carotenoids and composition of cocona (Solanum sessiliflorum Dunal), a wild Brazilian fruit. J Food Compos Anal 72:32–38
Shaheen S, Ahmad M, Haroon N (2017) Edible wild plants: alternative approach to food security. Springer, USA
Shameh S, Hosseini B, Alirezalu A, Maleki R (2018) Phytochemical composition and antioxidant activity of petals of six Rosa species from Iran. J AOAC Int 101(6):1788–1793
Shan S, Huang X, Shah MH, Abbasi AM (2019) Evaluation of polyphenolics content and antioxidant activity in edible wild fruits. BioMed Res Int Article ID 1381989

Shin T, Fujikawa K, Moe AZ, Uchiyama H (2018) Traditional knowledge of wild edible plants with special emphasis on medicinal uses in Southern Shan State, Myanmar. J Ethnobiol Ethnomed 14(1):1–13
Shrestha PM, Dhillion SS (2006) Diversity and traditional knowledge concerning wild food species in a locally managed forest in Nepal. Agrofor Syst 66(1):55–63
Stewart RR, Ali SI, Nasir E (1972) An annotated catalogue of the vascular plants of West Pakistan and Kashmir. Printed at Fakhri Print Press
Sundriyal M, Sundriyal RC (2004) Wild edible plants of the Sikkim Himalaya: marketing, value addition and implications for management. Econ Bot 58(2):300–315
Szentmihályi K, Vinkler P, Lakatos B, Illés V, Then M (2002) Rose hip (Rosa canina L.) oil obtained from waste hip seeds by different extraction methods. Bioresour Technol 82(2):195–201
Tariq A, Sadia S, Fan Y, Ali S, Amber R, Mussarat S, Ahmad M, Murad W, Zafar M, Adnan M (2020) Herbal medicines used to treat diabetes in Southern regions of Pakistan and their pharmacological evidence. J Herbal Med 21:100323
Teketay D, Lemenih M, Bekele T, Yemshaw Y, Feleke S, Tadesse W, Moges Y, Hunde T, Nigussie D (2010) Forest resources and challenges of sustainable forest management and conservation in Ethiopia. In: Degraded forests in Eastern Africa. Routledge, pp 31–75
Trichopoulou A (2007) Mediterranean diet, traditional foods, and health: evidence from the Greek EPIC cohort. Food Nutr Bull 28(2):236–240
Turan M, Kordali S, Zengin H, Dursun A, Sezen Y (2003) Macro and micro mineral content of some wild edible leaves consumed in Eastern Anatolia. Acta Agriculturae Scand Sect B-Plant Soil Sci 53(3):129–137
Valvi SR, Rathod VS (2011) Mineral composition of some wild edible fruits from Kolhapur district. Int J Appl Biol Pharm Technol 2(1):392–396
Vardavas C, Majchrzak D, Wagner K, Elmadfa I, Kafatos A (2006) Lipid concentrations of wild edible greens in Crete. Food Chem 99:822–834
Vekiari S, Ouzounidou G (2018) An overview of the wild plants consumed in the Island of Crete, Greece. Glob Perspect Underutilized Crops 259–285
Vrhovsek U, Guella G, Gasperotti M, Pojer E, Zancato M, Mattivi F (2012) Clarifying the identity of the main ellagitannin in the fruit of the strawberry, Fragaria vesca and Fragaria ananassa Duch. J Agric Food Chem 60(10):2507–2516
White BL, Howard LR, Prior RL (2010) Polyphenolic composition and antioxidant capacity of extruded cranberry pomace. J Agric Food Chem 58(7):4037–4042. https://doi.org/10.1021/jf902838b
Yamamoto T, Terakami S (2016) Genomics of pear and other Rosaceae fruit trees. Breed Sci 66(1):148–159
Yaseen G, Ahmad M, Shinwari S, Potter D, Zafar M, Zhang G, Shinwari ZK, Sultana S (2019) Medicinal plant diversity used for livelihood of public health in deserts and arid regions of Sindh-Pakistan. Pak J Bot 51(2):657–679

Dr. Sadia has completed her Ph.D. from the Department of Plant Sciences, Quaid-i-Azam University Islamabad, Pakistan. She is a researcher in the field of Botany and has published various many papers in various journals of good repute. Her fields of interest are plant biodiversity surveys, wild edible plants, medicinal plants, and systematics studies.

Prof. Dr. Ahmad is currently working as the Director of QAU Botanical Garden and Herbarium (ISL), Director of the Technology Science Park (QAU), and Chairman of the Department of Plant Sciences, Faculty of Biological Sciences, Quaid-i-Azam University, Islamabad, Pakistan. He has over 768 publications (citations ±12500, H-index 55, i10-index 287) in diverse fields of Plant Sciences, including 660 research publications, 23 books, and 18 book chapters. He has successfully supervised/produced 31 Ph.D. theses, 100 M.Phil., 55 M.Sc., and 10 BS research scholars in advanced areas of Plant Systematics and Biodiversity. He has also been given various national and international awards in recognition of his outstanding contributions in the areas of science and technology, including: Top 2% influential scientist of the World (2020); Young Research Scholar Award by HEC (2019); Highly Cited Research Paper Award by Elsevier and Willey (2019); Young scientist award by CAS–PIFI, China (2018); Young membership award by Pakistan Academy of Sciences (2016); Productive scientist awards by PCST (2009 to date); TTS Performance based Awards (2010 to date); Post Doc. Fellowship by TWAS-Malaysia (2012); Best book award by HEC (2013); Best research paper award by HEC (2011); and Gold Medal award by Pakistan Academy of Sciences (2011). He is a member of many international and national academic bodies. Dr. Ahmad has been awarded with many research grant projects funded by GBIF, BIFA (Japan-USA), NAS-USA, CAS-China, Mevlana-Turkey, PAS, HEC, and TWAS. These research grants helped him establish modern digital Herbarium (ISL), Botanical Garden, Technology Science Park, Melissopalynology, Aerobiology, and Nutraceutical and Green Biofuel research laboratories. He has organized 11 and attended 75 international/national conferences as keynote speaker. He has been hosted a series of TV programs and YouTube Channel (Miracle Herbal Diversity) to aware global and Pakistani communities, and to establish farmers linkages with academia and industries to use plant biodiversity for socio-economic uplifting.

Dr. Belgacem holds a Ph.D. in Biological Sciences and a M.Sc. in Natural Resources Management. His experience extends to more than 25 years in the area of arid and desert ecosystems in the MENA region. He joined the Food and Agriculture Organization of the United Nations (FAO) in Saudi Arabia as a Technical Adviser in November 2020. During 2011–2020, he was Rangeland Senior Scientist cum Regional Coordinator of the ICARDA program in the Arabian Peninsula (Dubai Office). He also served as a Head of the Rangeland Program and Director of Plant resources at The Arab Center for the Studies in Arid Zones and Dry Lands (ACSAD), Damascus, and Head of the Rangeland and Mapping Unit in the Institute of Arid Areas (IRA), Tunisia. He coordinated/participated in several research projects with the German Technical Cooperation (GIZ), European Union, IFAD, AFESD, ACSAD, FAO, OSS, and GCC on natural resources management, biodiversity conservation, combating desertification and adaptation to climate change, and rehabilitation and management of rangelands. He published more than 120 scientific research papers.

Dr. Zafar obtained his Ph.D. from Quaid-I-Azam University Islamabad, Pakistan in 2011. Currently, he is working as an Assistant Professor at the Department of Plant Sciences, Quaid-i-Azam University Islamabad, Pakistan. He is a renowned scientist in the field of medicinal plants, plant biodiversity, and renewable energy. He is the founder of the first nutraceutical and traditional medicinal plant laboratory as well as biofuel and biomass energy laboratory at Quaid-i-Azam University Islamabad, Pakistan. Dr. Zafar supervised 13 Ph.D. and 49 M.Phil. research scholars and is currently supervising 5 Ph.D. and 7 M.Phil. research students. He has published so far 415 research papers with a high impact factor and H index in international journals of repute and has above 10676 citations. Dr. Zafar has published 12 books and chapters in the field of medicinal plant biodiversity and energy technology. The Ministry of Science and Technology and Pakistan Academy of Sciences placed Dr. Zafar in the list of 10 most influential Pakistani young scientists and awarded him with a gold medal and a productive scientist award. His creative work at the university includes the establishment of a medicinal plant lab, biofuel lab, digital herbarium, botanical garden, and nutraceutical lab for research purposes and linkage with industries for rural and academic development. Dr. Zafar is an associate editor of various journals of repute a a member of many international societies like USEA, Pakistan Botanical Society, International Society of Ethnopharmacology, and Asian Biofuels. He has attended and organized more than 100 national and international conferences and delivered plenary lectures on medicinal plants and renewable energy technologies. Currently, he is linked with world-renowned institutes for collaboration regarding research and development in natural products from medicinal plants and biomass energy technologies.

Dr. Sultana is a scientist in the field of biodiversity and medicinal plants (nonedible oil seeds and herbal drugs). She has 205 research publications in top international journals, more than 5000 citations, with high IF, H and I indices. She has as well ten international books published and circulated internationally. Dr. Sultana is awardee of various national and international awards. She has been selected as the Young Lady from Pakistan by the Institute of Post Graduate studies, USM Malaysia, Higher Education Commission, and Pakistan Council for Science and Technology. She is also the editorial board member of several well-reputed ISI journals and book series. Currently, she is supervising and working on a number of research projects on natural plants products, new energy, and low carbon technology using biofuel and nonedible oil seeds for biodiesel production, and plant biodiversity and conservation.

Dr. Majeed is a PhD scholar in the field of Plant Sciences particularly his work expertise on Biodiversity and Plant Taxonomic Studies from Deserts areas of Pakistan. He has published research articles in various journals of good repute. Salman has participated a number of conferences held at national and International Level. His fields of interest are plant biodiversity, plant taxonomy, melissopalynology, medicinal plants, wild fruits, plant based biofuel technology, honey analysis and systematics studies.

Dr. Yaseen is a researcher in the field of Botany and Assistant Professor at Botany Department at University of Education Lahore, Pakistan. Currently, he has completed a Ph.D. from the Department of Plant Sciences, Quaid-i-Azam University Islamabad, Pakistan. He has published more than 60 research articles in various journals of good repute, 8 book chapters (especially in the field of medicinal plants used as food and medicine), and a book. Dr. Yaseen has organized 9 national and international conferences and participated in more than 20 conferences. Dr. Yaseen has worked as an Assistant Professor (IPFP) in the Department of Botany, PMAS Arid Agriculture University Rawalpindi, Pakistan. He has worked as a Visiting Faculty Member in the Department of Plant Sciences, Quaid-i-Azam University, Islamabad. He has thought various courses at BS and M.Sc. level. He serves in many journals as active reviewer and play important role in improvement of manuscripts. He also worked as a Research Associate in an International project on Digitization of Flora of Pakistan with special reference to Data mobilization and Georeferencing of Plant occurrence from Pakistan funded by GBIF. His fields of interest are plant biodiversity surveys, wild edible plants, their traditional knowledge, and food composition. He has a good expertise in management and digitization of Herbarium and has the capacity to develop and establish botanical garden.

The Potential of Coconut By-Products to Foster Food Security and Sustainability in Sri Lanka

Nazrim Marikkar and Muneeb M. Musthafa

Abstract Coconut (*Cocos nucifera* L.) is an important crop, mainly in the tropical and subtropical regions of the globe. It is one of the top ten useful trees in the world, providing food and non-food benefits to millions of people worldwide. As coconut is the second largest crop in extent next to staple crop 'Rice' in Sri Lanka, it plays a vital role in the household food security. The annual production of coconuts in the country is reported to be about 2.8 billion nuts, out of which 1.8 billion is used for household consumption, and the balance of 1 billion is being available for manufacture of coconut products. In recent times, factors like climate change, fragmentation of coconut lands, and prevalence of pest and diseases pose major risk for future coconut yield in the country. Maximizing the utilization of the coconut sector's by-products is proposed as a proactive approach to address coconut-based food insecurity in Sri Lanka. Coconut shell, coconut testa, coconut sap of the inflorescence, and mature coconut water released from factories are some of the by-products of coconut industry, showing great potential. Utilizing them for food purposes might entail various direct and indirect economic benefits and positive environmental impacts, while reducing disposal costs and increasing the value of the coconut tree.

Keywords Climate change impact · Coconut by-products · Food security · Sri Lanka · Sustainability

N. Marikkar (✉)
National Institute of Fundamental Studies, Hanthana Road, Kandy, Sri Lanka
e-mail: nazrim.ma@nifs.ac.lk

M. M. Musthafa
Department of Biosystems Technology, Faculty of Technology, South Eastern University of Sri Lanka, University Park, Sri Lanka
e-mail: muneeb@seu.ac.lk

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_12

1 Introduction

Coconut palm (*Cocos nucifera L.*), an important member of the family palmaceae, is grown in more than 90 countries worldwide, with a total production of 54 billion nuts per annum. Indonesia, being the world's largest producer of coconuts in recent times, contributed about 16,235 million nuts in the year 2018. India produced about 14,700 million nuts in the same year and became the second largest producer of coconut (FAOSTAT 2019). The steady growth of Indian coconut sector in recent times is mainly due to expansion of the cultivation into new areas as well as the increased productivity of coconut farming. The Philippines is the third largest producer of coconuts in recent times, but the world's biggest exporter of a range of coconut products (FAOSTAT 2019). Fresh coconut, desiccated coconut, copra meal, coconut milk powder, coconut water, liquid coconut milk, Nata de Coco, virgin coconut oil, etc., are some of the edible products, which bring large amount of foreign exchange to Sri Lanka.

Being a commodity, coconut plays a significant role as a means of livelihood and a source of national income to Sri Lanka. It is the second largest crop in extent in the country next to staple crop 'Rice.' The annual production of coconuts in Sri Lanka is reported to be about 2.8 billion nuts, out of which 1.8 billion is required for household consumption of fresh nuts, and the balance of only 1 billion is being available for manufacture of coconut products by industries (Dissanayeke 2005). In fact, the amount of coconuts remaining for industries to process various products is hardly sufficient in the present scenario. According to some estimates, at least 800 million more nuts are required to run the industries smoothly without shortage of raw material. A multitude of factors has remained as hurdle for the stagnation of nut production in Sri Lanka. The possibility of expansion of coconut cultivation beyond the traditional coconut triangle is limited due to various reasons. Climate change, fragmentation of coconut lands for other uses, and threats from pests and diseases are said to be some of the other significant factors which have contributed immensely to this situation.

1.1 Impacts of Climate Change

Climate change accompanied by extreme weather patterns is really a significant challenge to the entire agricultural system, both in Sri Lanka and elsewhere in the world. Since coconut is a rain-fed crop, climate change and extreme weather patterns would definitely affect the availability and utility of coconut in various spheres. Being a tropical country with seasonal rainfall, Sri Lanka has already witnessed the impact of drought on the annual nut yield. Particularly, the coconut cultivation in the dry and intermediate zones of Sri Lanka has been highly affected due to recurrent dry weather. According to data collected over several years, the inter-annual nut yield variation is well correlated with the rainfall pattern existing in the major coconut growing areas of Sri Lanka. As climate change impacts are expected to be prominent by 2050, there is likely a higher risk of drought-related water stress for coconut farming in Sri Lanka (Pathiraja et al. 2015). Past studies on climate change have showed the effect of daytime dry weather on the reduction of coconut yields. Based on coconut data from 1971 to 2001, about 60% variation in coconut production has been noticed due to climate-related factors. During the period from 1960 to 1990, an annual temperature increase of 0.016 °C has been observed across the whole country (Peiris et al. 2008). Not only the number of warm days and warm nights have increased, but also the average annual rainfall has dropped significantly during this period (Pathiraja et al. 2015). With the increase in temperature, the coconut yield has been severely affected. In order to ameliorate the severity of dry weather on coconut yield, the Coconut Research Institute of Sri Lanka recommended various countermeasures, such as mulching, rain water harvesting, and drip irrigation. The success of these measures depends heavily on the level of adoption by the stakeholders in the estate sector.

1.2 Impact of Land Fragmentation

Statistics of the past have shown that coconut occupies about 21% of the arable lands in Sri Lanka, which is almost 400,000 ha (Weerawardana et al. 2015; Pathiraja et al. 2015). Most of these lands are mainly concentrated in the districts of Puttalam, Kurunegala, and Gampaha due to various agro-climatic factors (Dissanayeke 2005). Coconut cultivation is tended to decline, especially in these three districts owing to a multitude of factors related to land fragmentation and lands being devoted for alternative uses. With the population growth, the demand for land to be used for housing construction and urban infrastructure development has steadily increased in the major coconut growing areas. Consequently, coconut estates are fragmented into small plots of land to create new residential areas and shopping complexes. While accomplishing this exercise, felling of coconut trees is done indiscriminately without giving due consideration for replanting in alternative areas. This trend has greatly contributed to the shortage of fresh nut availability for the local demand. Owing to a lack of coconuts, the coconut oil production was on the decline as producers of coconut oil were unable to run their factories in full operation. Although an expansion of the coconut cultivation had been reported in the dry-zone districts of Anuradhapura, Moneragala, and Polonnaruwa within the period 1982–2002, its contribution was still far below when compared to the increasing annual demand for coconuts (Dissanayeke 2005).

1.3 Impact of Pest and Diseases

Pests and diseases of coconut palms negatively impact the annual coconut production and food security in Sri Lanka. According to available studies, coconut palm is often attacked by a number of insect pests all around the year. Nearly 55 insect pests and mite species associated with the coconut palm have been identified in Sri Lanka (Fernando 2014). The tall nature of coconut palm poses a great challenge in conducting pest management practices effectively in the estate sector. The major pests of coconut such as coconut mite (*Aceria guerreronis* Keifer), coconut caterpillar (*Opisina arenosella* Walker1), red weevil (*Rhynchophorus ferrugineus* Olivier), Plesispa beetle (*Plesispa reichei* Chapuis), and black beetle (*Oryctes rhinoceros* Linnaeus) are prevalent in both the dry and wet zones (Fernando 2014). Among various pests, red weevil is widely considered as the most devastating insect pest, which affects coconut palms in most parts of the South and Southeast Asia (Kumara et al. 2015). Particularly, it can cause fatal damages to young coconut palms aging between 3 and 10 years. The coconut mite (*Aceria guerreronis* Keifer) is the next most important pest, which damages immature nuts of coconut palms causing serious yield losses. As coconut mite colonizes and feeds on the meristematic tissue beneath the bracts of the developing fruits, it would lead to immature nut fall and malformation of developing nuts. Previous studies showed that an economic loss of 10–13% would occur due to this pest attack (Wickramananda et al. 2007).

The leaf eating caterpillar known as *O. arenosella* is yet another serious pest of coconut which is prevalent in many coconut growing areas of the country. Extensive leaf damages by this pest lead to yield losses as this pest causes severe damage leading to the reduction of the rate of flower spikes and increases in the premature nut fall (Kumara et al. 2015). The black beetle, which is commonly known as rhinoceros's beetle, is prevalent in all parts of Sri Lanka all around the year. When compared to mature palm, young palms below five years of age are more prone to severe damages by this pest. The damages by the adult beetles feeding in the bud region of seedlings and young palms would cause severe setback in the growth of young coconut palms (Fernando 2014). Past surveys have already shown that 72% of coconut growers experience black beetle damage in their plantations (Peiris et al. 2006). Apart from pests, coconut palms are also vulnerable to plant diseases, such as leaf scorch, leaf wilt, and stem bleeding in recent years. A leaf wilt disease spread over the southern part of Sri Lanka during 2002–2006, affected roughly about 336,000 coconut palms (Wijesekara and Fernando 2013). As a short-term measure, most of these palms were uprooted to prevent the spread of this disease to other parts of the country.

2 Utilization of Coconut By-Products

2.1 Coconut Shell

Nutshell is one of the important components of the whole coconut. According to some estimates, per nutshell weight is about 12–14% of the total husked nut weight (Perera et al. 2014). As a solid by-product, coconut shell is reported to cause environmental unfriendliness to people living in major producing countries. It is a common knowledge that the coconut shell thrown in open yards is an ideal breeding ground for dengue mosquitoes. It is because of the fact that there is a high possibility for rain water being get collected in it. This may provide a conducive environment for the growth of mosquito larvae. When coconut shells are disposed by open burning, it will cause emission of greenhouse gases, known to contribute immensely to global warming.

Nevertheless, the negative environmental effects of nut shell can be minimized effectively by practicing more sustainable strategies. The use of agricultural waste receives more attention now due to the tendency to produce natural products from them (Raihana et al. 2015). The extraction of valuable bioactive natural products from agro-wastes has already been discussed extensively elsewhere in the literature (Kumar et al. 2017). In an early report, Thebo et al. (2016) demonstrated that the extracts of nutshell can be effective against human pathogenic fungi, including *Aspergillus niger, Aspergillus flavus, Trichophyton rubrum, Microsporum canis, Microsporum gypseum, Aspergillus fumigates, Trichophyton mentagrophyte,* and *Trichophyton vercossum.* The phyto-chemical constituents of the nutshell have been attributed to the above-mentioned bioactivities. Multiple reports have previously indicated that the major constituents of nutshell are cellulose, hemicelluloses, and lignin (Liyanage and Pieris 2015). The variability observed in chemical composition as well as the shell particle distribution was responsible for the mechanical and physical properties of coconut shell. The coconut shell particles as shown in Fig. 1, find applications in polymer and ceramic matrix composites, in activated carbon and charcoal powder production, and as filler in concrete reinforcement (Ikumapayi et al. 2020).

The nutshell has been the subject of several investigations leading to biofuel generation as well as production of activated carbons (Fig. 1). In many parts of Asia and Africa, the nutshells are used as a source of energy for industrial boilers while its usage as gravel for plantation road maintenance was remarkable. The nutshells are shown to be useful for the production of activated carbon, mosquito repellent coil, and as fillers in plastic. The ash of coconut shell consists mainly of chemical constituents, such as silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron (III) oxides, which are known to react with the product coming from the cement hydration process, providing additional strength to cementation (Sareena et al. 2012). A comparison of strength characteristics between coconut shell and palm kernel showed that the concrete of coconut shell has greater compressive strength than that made with palm kernel shell when mixing in the same proportions.

Fig. 1 Coconut (**a**), nutshell (**b**), shell powder (**c**), and charcoal powder (**d**). *Source* Photo by the authors

The partial combustion of coconut shell will yield charcoal, which is an industrially important raw material for several high-value end products. As an alternative path for open burning, partial burning of nutshell can be possible in a properly designed heat recovery vessel. This would not only reduce air pollution, but also help reuse the heat dissipating from the partial burning. The released carbon monoxide from this process could generate ample amount of heat, if subjected to further burning. The steam activation of charcoal would produce activated carbon, which has multiple industrial applications. Activated carbon produced from charcoal is used in a broad range of applications from industrial to residential uses that include drinking water purification, ground and municipal water treatment, power plant, and landfill gas emissions. Among different agro-waste materials utilized globally, coconut shell is reported to have produced the highest amount of activated carbon (Ikumapayi et al. 2020). Charcoal is commonly used as a fuel by fast-food industries, since it is a promising replacement for normal coal due to high heat capacity and nice fragrance produced during burning. Coconut charcoal has also been confirmed for its efficacy as a natural tooth whitener, promising purifier as well as a moisturizer.

2.2 *Coconut Testa*

Coconut testa (CT), which occurs as an outer brown layer of the fresh coconut kernel, is a rich source of oil. According to some previous studies, it is the part of the coconut kernel where oil is more concentrated (Marasinghe et al. 2019; Adekola et al. 2017).

Fig. 2 A dehydrated sample of coconut testa. *Source* Photo by the authors

As the removal of testa from the kernel is a requirement for the processing of products such as desiccated coconut, coconut cream, and milk powder, a substantial quantity of testa is generated on a daily basis by coconut factories (Fig. 2). Based on the fruit component study by Perera et al. (2014), it is claimed that about 6500 kg of wet CT can be generated out of 100,000 nuts of Sri Lankan tall variety. Hence, it is worthwhile to pay attention to maximize the use of this bio-waste in productive applications.

The flow chart in Fig. 3 depicts some of the important steps involved in the recovery of oil from CT. Since testa is the part of the fresh kernel used for oil extraction, the oil extracted traditionally is known as coconut testa oil (CTO) (Marikkar and Nasyrah 2012). The dehydration of CT is usually done either by sun drying or kiln drying. Large-scale producers, however, use mechanized dryers for the same purpose. During the oil extraction, the dried testa is disintegrated into smaller pieces prior to feeding into oil expellers. The crude oil extracted is subsequently subjected to sedimentation and filtration (Fig. 3).

The CTO is in fact a unique oil which might be mistaken as an ordinary coconut oil produced from dried copra. Despite the differences in the quality indices, the CTO has been synonymously used with ordinary coconut oil by local traders. Owing to this reason, researchers in the past attempted the application of principle component analysis to fatty acid data to distinguish CTO from ordinary coconut oil (Marikkar and Nasyrah 2012). The general quality characteristics of CTO would be slightly different from those of copra-derived oil as shown in Table 1. Generally, the FFA content of CTO supplied by oil milling industry might exceed the limit shown in Table 1.

According to Table 1, the fatty acid composition of CTO is also slightly different from that of the ordinary coconut oil, especially with regard to some unsaturated fatty acids. The CTO is usually found to have higher iodine value mainly due to the

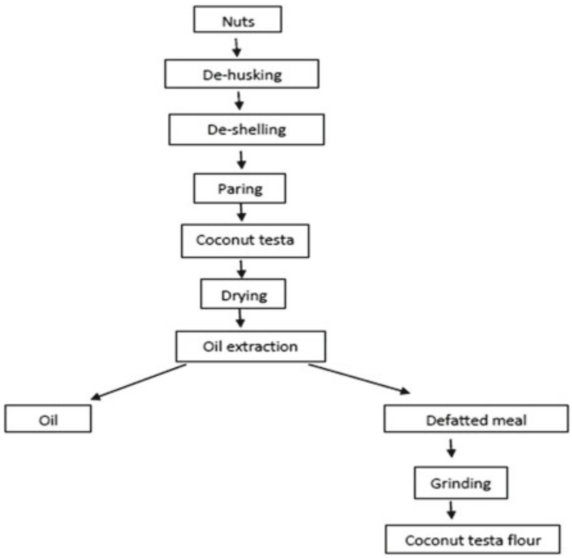


Fig. 3 Process flow chart of producing coconut testa oil and defatted testa flour

Table 1 Comparative chemical characteristics of ordinary coconut oil and coconut testa oil[1]

Parameter	Ordinary coconut oil	Coconut testa oil
Iodine value (Wijs)	7.6–10.0	15.5–16.9
Saponification value (mg KOH/Kg)	>250	>250
Unsaponifiable matter (%)	0.80	0.8
Free fatty acid (%)	<0.8	<0.8
Fatty acid composition		
C6:0	0.52	0.12
C8:0	4.50	3.14
C10:0	4.20	3.15
C12:0	48.60	38.60
C14:0	21.20	21.67
C16:0	9.10	12.67
C18:0	2.80	4.12
C18:1	5.80	14.22
C18:2	2.60	2.15
C18:3	Tr	Tr
MCFA (%)	57.82	45.01
LCSFA (%)	33.10	38.46

[1]Abbreviations: Tr., trace level, MCFA, medium chain fatty acid, LCSFA, long chain saturated fatty acid, *Source* Marikkar et al. (2007)

increased amounts of oleic ($C_{18:1}$) and linoleic ($C_{18:2}$) acids (Table 1). As a result, the oxidative stability of CTO is expected to be slightly lower than that of ordinary coconut oil. This feature should be given consideration when using CTO as a frying medium in preparation of foods meant to be kept on shelves for months. Food regulatory authorities operating in several countries have given guidelines regarding the tolerable limits of acid value and peroxide value in frying oils. During deep frying, the oxidation process becomes more vigorous and leads to the development of rancid smell in the fried products (Marikkar et al. 2007). In these situations, the addition of little amounts of anti-oxidants such as rosemary and sage extracts would be desirable.

The extraction of CTO, as depicted in Fig. 3, would lead to the generation of an edible grade defatted residue as a by-product. The defatted residue from CT could be crushed into powder form (CTF), which showed good functional properties (Marasinghe et al. 2021). A comparative analysis of the physicochemical and functional properties of wheat flour (WF) and CT flours [CTF] displayed differences in almost all properties including swelling capacity, water absorption capacity, oil absorption capacity, emulsion activity, bulk density, etc. (Table 2). As a noteworthy feature, the swelling capacity of CTF (30) was higher than WF (20). According to Suresh and Samsher (2013), swelling capacity of flour may be influenced by varietal differences, particle size differences, and processing methods. According to Table 2, the bulk density of CTF (0.66) was slightly higher than that of WF (0.49). The bulk density (g/cm^3) of flour is defined as the density measured without the influence of any compression (Chandra et al. 2015). Lam et al. (2008), previously stated that the bulk density of flour samples depends on particle size, density of individual particle, moisture, and surface characteristics, which are generally influenced by the preparation method. Undoubtedly, the preparation methods of CTF and WF were not similar as WF was cereal-based while CTF was non-cereal-based. According to Suresh and Samsher (2013), the high bulk density of flour suggests its suitability for multiple uses in food preparations.

The water absorption capacity of WF and CTF were 65% and 75%, respectively (Table 2). Berton et al. (2002) stated that the water absorption capacity is associated with protein and starch contents of flour. In fact, the protein and crude fiber contents of CTF were relatively higher than those of WF (Table 2). As the ability of protein to enhance the formation and stabilization of emulsions is important for many applications, information on emulsion activity of flour is beneficial (Cauvain and Young 2006). As shown in Table 2, the emulsion activity of CTF was lower (25) than WF (50). Some of the previous researchers found that the emulsion activity of flour would increase with higher amounts of soluble proteins (Garba and Kaur 2014) and reduce with fiber content. The increased crude fiber content, as noticed before in CTF, could be a probable reason for the lower emulsion activity displayed by CTF.

Foods with high dietary fiber content are highly regarded as diets for patients suffering from diabetes mellitus (Trinidad et al. 2001). According to some previous studies, the coconut flour from residue left after coconut milk extraction was reported to have 60.9% total dietary fiber, 56.8% insoluble dietary fiber, and 3.8% soluble dietary fiber per 100 g of flour (Gunathilake et al. 2009; Trinidad et al. 2001). Rushdah et al. (2022) found that CTF had 68.74–72.87% total dietary fiber, 53.18–55.85%

Table 2 Functional and nutritional properties of CTF and WF

Functional/Nutritional properties	Flour-type	
	CTF	WF
Swelling capacity (ml)	30	20
Water absorption capacity (%)	75	65
Oil absorption capacity (%)	52.7	58.50
Emulsion activity (%)	25	50
Least gelation concentration (%, w/v)	18	8
Bulk density (g/cc)	0.66	0.49
Moisture (%)	2.27	14.0
Ash (%)	4.50	1.82
Protein (%)	23.82	11.68
Fat (%)	10.17	1.91
Total carbohydrate (by difference)	59.24	70.59

Source Marasinghe et al. (2019) and Marikkar et al. (2020)

insoluble dietary fiber, and 13.65–18.05% soluble dietary fiber per 100 g of flour. This suggested its suitability in formulating low-calorie snacks and breakfast cereals for diabetes patients.

Cookies are hardly regarded as a healthy snack because of their high levels of rapidly digestible carbohydrate, high fat content, low levels of fiber, and only modest amounts of protein (Klunklin and Savage 2018). As the distribution of soluble and non-soluble dietary fiber of CTF is encouraging, Marikkar et al. (2020) investigated the substitution of WF with CTF in preparation of cookies. Wheat flour substitution up to 30% by CTF was possible without affecting the overall acceptability of cookies (Marikkar et al. 2020). With increasing level of substitution, the fiber and protein contents were increased while the amylose content and hardness of the cookies were decreased. In another study, formulations of string hoppers incorporated with CTF were done by mixing white rice flour (RF) with CTF in four different ratios: F_1 (RF: CTF = 70:30); F_2 (RF: CTF = 75:25); F_3 (RF: CTF = 80:20); and F_4 (RF: CTF = 85:15) (Rushdah et al. 2022). Likewise, the formulation of flat-bread rotti was done by mixing wheat flour (WF) with CTF in four different ratios: P_1 (WF: CTF = 60:40); P_2 (WF: CTF = 70:30); P_3 (WF: CTF = 80:20); and P_4 (WF: CTF = 90:10). According to sensory evaluation, the highest score of overall acceptability and other sensory attributes were observed for composite flour mixtures incorporated with 25% of CTF in rice flour for string hoppers (idiyappa), and 20% of CTF in wheat flour for flat-bread (rotti) (Rushdah et al. 2022).

2.3 Utilization of Mature Nut Water

Coconut water from young coconut is well known as a delectable drink to quench thirst. In contrast, the taste of mature nut water might differ considerably from that of the tender nut water due to changes in composition and other chemical parameters. With increasing maturity of nuts, pH of nut water might change and the concentration of total sugars may decline leading to the changes in sweetness (Ranasinghe et al. 2003). Even many more changes might be possible in the taste of the mature nut water collected from coconuts, which have undergone more than three weeks of seasoning. It is understood that the changes in pH and titrable acidity during prolong storage in open yards could be the probable reason. According to past experience, nut water released from copra, desiccated coconut, and milk-producing industries look turbid in appearance as the pH is found to be in the range of 6–7. As they are unpalatable, coconut processing industries are often compelled to discard them without any productive use. In most cases, nut water gets mixed with the process wash water of mills and discarded into nearby streams or ponds, leading to environmental pollution.

As mature coconut water contains about 2.5–3.0% sugar, it can be utilized as a fermentation substrate for producing vinegar. Since the amount of fermentable sugars present in the starting material is fairly low, it is needed to be supplemented with added sugar derived from low-cost sources. The vinegar production usually involves a dual-stage fermentation process, in which sugars are converted initially to ethanol by the action of yeast (*Saccharomyces cerevisiae*) in anaerobic fermentation. In the second stage of fermentation, the Acetobacter oxidizes ethanol into acetic acid (Gunathilake and Fernando 2007). Although the alcoholic fermentation step of the vinegar process is faster (4–5 days), the acetic fermentation step might take about 2–3 months for completion. To accelerate the vinegar formation, a generator process has been devised to maximize the surface exposure of fermented nut water into oxygen. This would enhance the air supply for acetobacter to oxidize ethanol into acetic acid efficiently. With the recycling of the stock solution, the total fermentation time can be reduced to 1–2 weeks. When the vinegar reaches its maximum strength, the acidity would be around 4%. The acetified vinegar is usually allowed to aging before bottling (Gunathilake and Fernando 2007).

2.4 Coconut Sap Liquid

A sugar-rich fluid called coconut sap drips out, when cutting the edge of an unopened inflorescence of coconut trees. This out-flowing sap can be collected either into a clay pot or a polythene bag (Fig. 4). The unfermented sap may contain sucrose, proteins, vitamins, and minerals. As the sap has about 13–15% of sugar, it may be converted into brown sugar, which is useful as an alternative for cane sugar used in Sri Lanka.

Fig. 4 Coconut sap collection from the inflorescence of coconut palm. *Source* Photo by the authors

Of the total sugars present in the fresh sap, sucrose is always the most dominant constituent, followed by fructose and glucose (Purnomo and Mufida 2004).

Naturally, the sap that drips out of the inflorescence might undergo hydrolysis by the invertase activity, which would negatively impact brown sugar formation. If the solid brown sugar product is desired from coconut sap, it may be necessary to take some precautionary measures to retard the invertase activity as well as fermentation. In the rural Sri Lanka, smoke curing and adding little slaked lime into the collection pot are practiced to prevent fermentation. This might have helped minimize the microbial activity by maintaining the pH of the sap within the basic range. Alternatively, sodium meta-bisulfide in place of slaked lime can be used for the preservation of coconut sap (Samarajeewa et al. 1985). Food additives, such as para-hydroxy benzoate, benzoic acid, and potassium sorbate are said to display some effectiveness in controlling the fermentation of coconut sap. However, the use of some of these substances in food applications is restricted on the grounds of food safety concerns. Hence, several plant materials are being used by village folk to preserve coconut sap during the time of collection. For instance, finely cut dried stem-bark of 'Hal' tree (*Vateria Copallifera*) is popularly used in Sri Lanka to preserve coconut sap. According to some studies, the dried exocarp of mangosteen (*Garcinia mangostana*) fruit could also be added into sap collection pot for the same purpose (Purnomo and Mufida 2004). The anti-ferment activity of these plant materials is believed to be related to some bioactive constituents present in them (Joze et al. 2008; Gunawardane et al. 1986).

Besides the preventive measures to arrest fermentation, it may also be necessary to cross-check the suitability of coconut sap before processing. Some studies showed that an instant acidity test using litmus paper would be useful in this regard. The coconut sap displaying a pH value above 5.5 would be ideal for producing solid brown sugar while those displaying below this value would be suitable for coconut treacle or brown syrup. For the production of sugary products, the preserved sap is boiled in open pans at 105 °C. When the boiling is continued uninterruptedly, the solution would normally become more viscous. Depending on the ratio between sucrose and reducing sugars, the sap may be turned either into brown sugar or sap syrup. On average, 150 g of brown sugar can be recovered from a liter of coconut sap. Brown sugar from coconut sap has been widely used as an ingredient in several Indonesian culinary preparations, mainly due to the specific taste and flavors imparted onto end products. For instance, it is an important ingredient for sweet soy sauce (kecap manis) and intermediate moist meat (dendeng) in Indonesia (Purnomo 2007). The sap samples displaying pH below 4 would have undergone considerable fermentation, and become suitable as a raw material for fermented products such as arrack and vinegar (Jayasekara 1997).

If coconut sap is left over a period of time, it may become fermented, leading to an alcohol drink locally known as '*toddy*.' This fermentation process proceeds through three steps: an initial lactic acid fermentation; a middle alcoholic fermentation; and finally acetic fermentation. Analysis showed that only sucrose, fructose, and glucose were detected during the early stage of natural fermentation lasting about 7 h (Xia et al. 2011). However, almost no sucrose was detected after 58 h of natural fermentation. The ethanol content increased significantly from day 1 to day 5 of fermentation and achieved its maximum of 90 g/kg at day 7, but it was found to be decreasing in the later stage (Xia et al. 2011). The total acidity increased constantly from day 1 to day 3; the acids present in the fermenting sap include lactic, acetic, tartaric, malic, and citric acids, but the volatile acid mainly consists of acetic acid (Xia et al. 2011). If the fermentation is allowed to proceed to the third stage, a condiment called vinegar is produced. This is commonly used as an important preservative in food processing.

3 Concluding Remarks

Coconut is a multi-purpose tree crop with several benefits to human kind. Characterization of various components of coconut tree and its fruits established coconut's uniqueness to foster food security. One of the important approaches to face food shortage is to maximize the use of industrial by-products to produce edible and non-edible goods. The kernel of the coconut fruit is found to contain all macro- and micro-nutrients required for human diet. Thus, it can help overcome nutritional insecurity. Coconut testa left after food processing is one of the by-products and can be used to produce coconut testa oil, which can supplement partly for the annual requirement of coconut oil in the country. Coconut testa flour produced from the residue left after the extraction of oil can be supplemented with wheat flour to make low-glycemic food products. It was demonstrated that string hoppers (idiyappa) and flat-bread (rotti) of acceptable quality could be prepared using composite flour mixtures of 25% of coconut testa flour in rice flour and 20% of coconut testa flour in wheat flour, respectively. Coconut sap dripping out of the inflorescence when cut open can be used to produce coconut wine, brown sugar, syrup, and honey. These sweeteners can be used to supplement annual requirement of cane sugar in the country. The mature coconut water released from food processing industries is a potential raw material to produce coconut vinegar, a valuable food preservative. A host of other by-products available from coconut tree and its fruit could help address challenges induced by climate change. Nutshell, for example, is one of the important components of the whole coconut. When subjected to control combustion, it can help produce heat as well as charcoal. Coconut charcoal can be converted to activated carbon, which is used in a broad range of applications from industrial to residential uses.

References

Adekola KA, Salleh AB, Zaidan UH, Azlan A, Chiavaro E, Paciulli M, Marikkar JMN (2017) Total phenolic content, antioxidative and antidiabetic properties of coconut (*Cocos nuceifera* L) testa and selected bean seed coats. Ital J Food Sci 29:742–753

Berton B, Scher J, Villieras F, Hardy J (2002) Measurement of hydration capacity of wheat flour: influence of composition and physical characteristics. Powder Technol 128:326

Cauvain S, Young L (2006) Ingredients and their influences. In: Cauvain S, Young L (eds) Baked products: science, technology and practice. Blackwell Publishing Group, Oxford, p 72

Chandra S, Singh S, Kumari D (2015) Evaluation of functional properties of composite flours and sensorial attributes of composite flour biscuits. J Food Sci Technol 52:3681

Dissanayeke AMU (2005) Progress of coconut cultivation 1962–2002. Department of Census and Statistics, Sri Lanka

FAOSTAT (2019) Food and agricultural organization Stat. Available online at https://www.fao.org/faostat/en/#data Accessed on 20 Sept 2021

Fernando LCP (2014) Integrated management of major coconut pests and diseases in Sri Lanka. Accessed on https://library.apccsec.org › paneladmin

Garba U, Kaur S (2014) Review-protein isolates: production, functional properties and application. Int Res J Chem 4:22

Gunathilake KDPP, Fernando JAKM (2007) Development of low cost coconut water vinegar making process and evaluation of 'Generator Process' to accelerate the acetification. In: Proceeding of the international conference on biotechnology engineering. Kuala Lumpur.

Gunathilake KDPP, Yalegama C, Kumara AAN (2009) Use of coconut flour as a source of protein and dietary fiber in wheat bread. Asian J Food Agro-Ind 2:382–391

Gunawardane YAGP, Sotheeswaran S, Sultanbawa MUS, Surendrakumar S, Bladon P (1986) Another antibacterial polyphenol, cipelliferol B, from *Vateria copallifera* (dipterocarpaceae). Phytochemistry 25:1498–1500

Ikumapayi OM, Akinlabi E, Mujumdat JD, Akilabi S (2020) Applications of coconut shell/ash particles in modern manufacturing: a case study of friction stir processing. In: Modern manufacturing processes. https://doi.org/10.1016/B978-0-12-819496-6.00004-X

Jayasekara C (1997) Report of the coconut processing research division. In: Annual report of the Coconut Research Institute of Sri Lanka.

Joze PC, Neomi CR, Marisol OI, Jazmin MP (2008) Medicinal properties of mangosteen (*Garciana mangostana*). Food Chem Toxicol 46:3227–3239

Klunklin W, Savage G (2018) Biscuit: a substitution of wheat flour with purple rice flour. Adv Food Sci Eng 2:81

Kumar K, Yadav AN, Kumar V, Vyas P, Dhaliwal HS (2017) Food waste: a potential bio resource for extraction of nutraceuticals and bioactive compounds. Bioresour Bioprocess 4:18

Kumara ADNT, Chandrashekharaiah M, Kandakoor SB, Chakravarthy AK (2015) Status and management of three major pests of coconut in the tropics and subtropics. In: Chakravarthy

AK (ed) New horizons in insect science: towards sustainable pest management. pp 350–381. https://doi.org/10.1007/978-81-322-2089-3_32

Lam PS, Sokhansanj S, Bi X, Lim CJ, Naimi LJ, Hoque M, Mani S, Womac AR, Narayan S, Ye XP (2008) Bulk density of wet and dry wheat straw and switch grass particles. Appl Eng Agric 24:351

Liyanage CD, Pieris M (2015) A physico-chemical analysis of coconut shell powder. Procidia Chem 16:222–228

Marasinghe SSK, Marikkar JMN, Yalegama C, Wimalasiri S, Seneviratne G, Weerasooriya R, Liyanage R (2019) Comparison of inter-varietal differences in chemical composition and nutritional properties of coconut testa flour. J Natl Sci Found 47:349–356

Marasinghe SSK, Marikkar JMN, Yalegama C, Hewapathirana HPTD (2021) The physical and functional properties of partially defatted coconut testa flour. Int J Coconut Res Dev 37:1–12

Marikkar JMN, Nasyrah AR (2012) Distinguishing coconut oil from coconut pairing oil using principle component analysis of fatty acid data. Int J Coconut Res Dev 28:9–13

Marikkar JMN, Jayasundera JMMA, Prasadika AAM, Jayasinghe CLV, Premakumara GS (2007) Assessment of the stability of virgin coconut oil during deep-frying. Int J Coconut Res Dev 23:62–70

Marikkar JMN, Nagaraja R, Somawathie KMS, Hewapathirana HPTD, Yalagama CP, Littardi P, Chiavaro E (2020) Effect of coconut testa flour on cookie characteristics. Ital J Food Sci 32:209–221

Pathiraja PMEK, Griffith GR, Farquharson RJ, Faggian R (2015) The Sri Lankan coconut industry: current status and future prospects in a changing climate. Australasian agribusiness perspectives, paper 106

Peiris TSG, Bandaranayake NPAD, Fernando MTN (2006) Coconut research development and dissemination of technologies survey—growers perception

Peiris TSG, Hansen JW, Zubair L (2008) Use of seasonal climate information to predict coconut production in Sri Lanka. Int J Climatol 28:103–110. https://doi.org/10.1002/joc.1517

Perera SACN, Dissanayeke HDMAC, Herath HNMB, Meegahakumbura MGMK, Perera L (2014) Quantitative characterization of nut yield and fruit components in indigenous coconut germplasm of Sri Lanka. Int J Biodivers 24:740592

Purnomo H (2007) Volatile components of coconut fresh sap, sap syrup and coconut sugar. ASEAN Food J 14:45–49

Purnomo H, Mufida LH (2004) Sugar components of fresh sap and sap syrup of coconut. ASEAN Food J 13:159–163

Raihana ARN, Marikkar JMN, Amin I, Shuhaimi M (2015) A review on food values of selected tropical fruits' seeds. Int J Food Prop 18:2380–2392

Ranasinghe CS, Wimalasekara R, de Saram PSA, Fernando WPKF (2003) Preservation of young king coconuts (*Cocos nucifera* var. aurantiaca) during simulated sea shipment. ASEAN Food J 12:175–181

Rushdah SAF, Ulpathakumbura BSK, Yaalegama C, Hewapathirana DT, Marikkar JMN (2022) Evaluation of staple foods supplemented with defatted coconut testa flour. Int J Coconut Res Dev (in press)

Samarajeewa U, Mathes DT, Wijeratne MCP, Warnakula T (1985) Effect of sodium metabisulphide on ethanol production in coconut inflorescence sap. Food Microbiol 2:11–17

Sareena C, Ramesan MT, Purushothaman E (2012) Utilization of coconut shell powder as a novel filler in natural rubber. J Reinf Plast Compos 31:533–547

Suresh C, Samsher (2013) Assessment of functional properties of different flours. Afr J Agric Res 8:4849

Thebo NK, Simair AA, Mangrio GS, Ansari KA, Bhuto AA, Lu C, Sheik WA (2016) Antifungal potential and antioxidant efficacy in the shell extract of *Cocos nucifera* L. against pathogenic dermal mycosis. Medicines 3:12. https://doi.org/10.3390/medicines3020012

Trinidad TP, Valdez DH, Mallillin AC, Askali FC, Maglaya AS, Chua MT, Castillo JC, Loyola AS, Masa DB (2001) Coconut flour from residue—a good source of dietary fibre. Indian Coconut J 32:9–13

Weerawardana WPTD, Jayasinghe-Mudalige UK, Pathiraja PMEK, Jayalath KVNN (2015) Coconut land fragmentation in Sri Lanka: an inquiry into the potential moral hazard behavior of landowners seeking for the approval. J Coconut Res Inst Sri Lanka 20:39–48

Wickramananda IR, Peiris TSG, Fernando MTN, Fernando LCP, Edgington S (2007) Impact of coconut mite (*Aceria guerreronis* Keifer) on the coconut industry in Sri Lanka. Int J Coconut Res Dev 23:1–16

Wijesekara HTR, Fernando LCP (2013) Symptoms and etiology of Weligama coconut leaf wilt disease. In: Paper presented at the Weligama coconut leaf wilt disease: six years after. Coconut Research Institute of Sri Lanka

Xia Q, Li R, Zhao S, Chen W, Chen H, Xin B, Huang Y, Tang M (2011) Chemical composition changes of post-harvest coconut inflorescence sap during natural fermentation. Afr J Biotech 10:14999–15005

Dr. Nazrim Marikkar is an Associate Research Professor and currently the Head of Food Chemistry Laboratory at the National Institute of Fundamental Studies, Sri Lanka. He earned his Ph.D. in food chemistry from University Putra Malaysia in 2004. He has published research work extensively in the area of food authentication and anti-diabetic dietary formulations. Dr. Marikkar holds professional membership of the Institute of Chemistry, Sri Lanka and the Malaysian Institute of Food Technology.

Dr. Muneeb M. Musthafa is a Senior Lecturer attached to the Department of Biosystems Technology, Southeastern University of Sri Lanka. He received his Ph.D. in ecology and biodiversity from University of Malaya in 2018. During his postgraduate studies, he obtained a fellowship under international Graduate Research Assistant Scheme (iGRAS) of University of Malaya and a scholarship from Chinese Academy of Agricultural Sciences (CAAS). Dr. Muneeb has published more than 45 peer reviewed and indexed articles on various aspects, including ecology, biodiversity, genetic diversity, environmental conservation, food science and technology, etc. He is a professional member of the Entomological Society of Malaysia.

Potential of the Medicinal Flora in Pakistan and the Risk of Extinction: The Need for a Conservation Strategy

Ijaz Rasool Noorka, Mohamed Behnassi, Zafar Iqbal Khan, Hafeez-Ul-Hassan, Emran Manzoor, and Syed Shujat Ali

Abstract The medicinal flora has a prime importance from ancient times. 10% of the known plant species are used to cure human and animal diseases. In Pakistan, a large population depend on plants for the cure of major and minor diseases. These plants are wild, and some are cultivated like field crops. The livelihood of a large segment of population is connected with them. However, the important therapeutic flora species are going to extinct in the country due to many factors, particularly the over-collection by unauthorized people and the lack of a conservation strategy and a proper maintenance system. Therefore, local populations should be sensitized on the importance of growing essential medicinal flora. The present raw utilization of medicinal herbs in Pakistan and their prime conservation as income resources should be a key concern for research, business, and policy making.

Keywords Conservation · Health · Livelihood · Medicinal flora · Pakistan

1 Introduction

Medicinal plants are an important source of pharmaceutical agriculture. Such plants have a large importance, especially for desert and hilly areas and the coast. They

I. R. Noorka (✉)
Professor, Department of Plant Breeding and Genetics, Ghazi University, Dera Ghazi Khan, Pakistan
e-mail: ijazphd@yahoo.com

I. R. Noorka · Hafeez-Ul-Hassan · E. Manzoor · S. S. Ali
Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Sargodha, Pakistan

M. Behnassi
Economic Social & Environmental Council (ESEC), Center for Environment, Human Security & Governance (CERES), Rabat, Morocco
e-mail: behnassi@gmail.com; m.behnassi@uiz.ac.ma

Z. I. Khan
Department of Botany, University of Sargodha, Sargodha, Pakistan
e-mail: zafar.khan@uos.edu.pk

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_13

are commonly used by local populations for curing diseases from pre-historic times. Synthetic medicines reduce the use of medicinal plants, but over time they may have serious residual effects. Indeed, the allopathic medicines' action is quick, but after curing a chronic disease, they may cause other health issues like blood pressure fluctuations and stomach and liver problems. In some cases, microbes develop a certain resistance against synthetic medicines whose prices are often inaccessible for the poor. Recently, many peoples all over the world are turning toward natural resources for cure given their potential as a source of vitamins, antioxidants, and other medicinal virtues.

Presently, the medical research showed that the study of medicinal plants' biological activities is essential. Therefore, the production of new molecules from herbs that may be effective tools for curing dangerous diseases is expected. Indeed, many scientists have reported that some diseases like cancer can be cured by the use of natural resources. *Terminalia arjuna* and flavonoids, for instance, have shown effectiveness against cancer. *Eugenia jambolanare, Trigonella foenum, Allium sativum,* and *Allium cepa* are hypoglycemic herbs or shrubs with an effective result against diabetes mellitus, which affects many peoples in developing countries. Heart and vessels-related diseases are more common these days and cause more deaths all over the world, whereas herbal medicines are more effective against them. Arthritis and aging effects can be reduced by the use of herbal medicines given their enzymatic actions. Many plants are used to cure ulcer given their antioxidant and antimicrobial potential (Ali and Qaisar 2009). Scientists commonly separate phytochemical compounds (such as morphine, atropine, aconitine, nicotine, and atisine) from medicinal herbs; the latter are very active against a number of diseases.

With the progress made in herbal medicine research, this becomes an alternative effective source of health care in today's allopathic era marked by the science-based, modern medicine. The reason behind the use of medicinal plants is that they have a combination of side-effect neutralizing and synergistic combinations. Different plants are harvested commercially for the extraction of active ingredients. For the preparation of compounds and extracts, eastern medicines are largely based on Unani methods.

According to the World Health Organization (WHO), the use of herbal medicine is globally increasing. In developing countries, about 80% of peoples depend on these herbs to cure basic health issues. In developed countries, up to 65% of populations like to use alternative natural herbal medicines. More specifically, the percentage of people using herbal medicines in developing countries is, for instance, 60% in Tanzania, 80% in Benin, 70% in India, 90% in Ethiopia, and 60% Uganda, while the percentage in developed countries is 60–70% in Japan, 49% in France, 40% in The United States, 70% in Canada, 48% in Australia, and 31% in Belgium.

In present time, the global market of herbal medicines is US $60,000 million that may grow by US $5 trillion up to 2050. The growing trend to use herbal medicines has enhanced the acceptance of WHO rules about herbal medicines by governments. In The United States and Germany, for instance, the establishment of herbal medicine research institutes entails promising perspectives for this field in the future.

Many peoples are involved in the collection (especially women), processing, and marketing of such plants globally (Elisabetsky and Castilhos 1990). The medicinal flora is also an important source of income, especially in vulnerable rural areas.

Against such a background, this chapter highlights the importance and the scope of medicinal plants both globally and at the level of Pakistan, identifies the main factors threatening the sustainability of such plants, and assesses the progress made in herbal medicine research in Pakistan. The chapter concludes by developing some recommended measures to protect medicinal plants in the country given their growing social and economic importance.

2 The Global Demand and Supply of Herbal Medicines

There is an increasing interest for the natural medicine production and research, especially from pharmaceutical companies and research centers. Globally, the use of herbal medicine increases according to a growing trend and its active role in R&D and the culture of the community is also enhanced. This increasing consumption of herbal medicines shows the importance of using natural ways of cure.

In The United States, the botanical market is estimated at approximately US $1.6 billion per annum, which includes medicinal plants and herbs. The European countries import medicinal flora from Africa and Asia (around 400.000 tons annually costing about US $1 billion). The European Union (EU) utilizes 3000 kg *Glycerrhiza* annually. To secure such amount, 400 tons in the active plant parts and plant roots are required. China and India are the leading exporters, respectively. In China, during 2000, the output value of the pharmaceutical industry was US $28 billion. In 2010, the share of Chinese herbal medicine in the world market has reached 15%. In India only, the Lucknow produces medicinal plants of Rs. 90 millions annually. The Russians use 50,000 tons of medicinal plants annually, from which 50% are cultivated and the rest is widely collected. All these examples show that the cultivation medicinal plants are becoming globally essential to meet increasing demands. However, in Pakistan, the situation is reverse because there are no innovations in the area of cultivation of medicinal plants at both commercial and domestic levels.

Research projects running by different organizations in Pakistan regarding the conservation and utilization of plant genetic resources are playing a key role. The World Wide Fund for Nature (WWF) is playing leading role in this regard. It is also dealing with the conservation of endemic knowledge. In this area, there is a potential for agricultural production by the cultivation of medicinal plants of high value like Safran, which is an important and costly medicinal and aromatic agent, a sacred plant among many Muslims. In recent era, the annual yield and price of Safran have increased manifold. Its production per year was increased from 70,000 to 200,000 flowers yield. Qarshi Herbal Industries utilize 20 kg in 2002 in the medicines compared to 35 kg in 2009. One acre of land may yield a profit of >Rs. 100,000. Safran, often grown in tropical climate, is a very high profit crop for farmers in northern areas.

For all the reasons mentioned above, through the development of herbal medicine sector, many developing economies may access to promising market opportunities. To satisfy the increasing demand in this sector and exploiting new resources, new research programs and surveys are being undertaken.

3 Medicinal Plants in Pakistan and Their Scope

The total area of Pakistan is 796,096 km^2, and its climate varies from glaciers to desert. There is a large diversity of medicinal flora present from 0 to 8611 m altitude. It has been reported that 70% spp. of total species are climate specific, while 30% are multi-climatic. The country has four medicinal phytogeographical zones: Irano-Turanian (45%); Sino-Himalayan (10%); Saharo-Sindian (9.5%); and Indian element (6%) (Ali and Qaisar 2009).

Indeed, the geographical structure of Pakistan is very rich with a variety of medicinal flora due to a range of different climates and altitudes from glaciers to deserts and the coast. Such medicinal flora is well grown according to their ideal climate, and they are playing important roles in the agriculture of hilly areas and desert. The main regions of herb production are the northern areas, Murree Hills, Mansehra, Abbottabad, Sindh, Azad Kashmir, Baluchistan, Punjab, and KPK of Pakistan.

Many medicinal plants from the northern areas of Pakistan had been identified and listed by Gilani et al. (2009) and Hamayun et al. (2006). Similarly, there are 70 spp. of medicinal plants studied and reported from Mansehra, KPK province, by Haq and Hussein (1993). In Ayubia National Park, Nathiagali, and Swat, ethnobotanical studies of medicinal were conducted by Shinwari et al. (2003). 83 species, that were locally used in Chitral areas of Hindukush range, were scientifically studied by Ali and Qaisar (2009). In addition, 114 spp. with ethnobotanical uses had been reported from Balochistan and in Kharan. With the listing of such plants, their chemical and ethnobotanical properties, along with their medicinal uses, had been identified (Kirba et al. 2009).

Generally, it was observed that there are 6000 species of plants found in Pakistan (Stewart 1972), 4200 of which are used as medicinal plants, 75 unprocessed drugs are exported, and 200 species are processed within the country. Hazara and Malakand are the leading producer with a potential of 500 tons of medicinal plants (24 tons in Northern Areas, 38 tons in Azad Kashmir, and 16 tons in Murree Hills).

In Pakistan, the demand for medicinal herbs is 20,000 tons/annum while the production is low. This gap is either met by imports or by increasing domestic production through incentivizing farmers to grow medicinal plants at commercial scales. However, the imbalance between import and export of medicinal plants is still very substantial. To reduce this gap, the Central Board of Revenue (CBR) announced in 2001 the duty-free import of medicinal plants.

12% of Pakistani medicinal plants are used as medicines, and about 300 species are exported. Ten leading *Dar-ul-hikmats* in the country use more than 2 million kg annually of 200 species during 1990s, and the consumption has increased manifold at present time. According to a survey, 22 spp. of plants with a value of USD 0.8 million were traded in 1990, and in 2002, the value has reached USD 6.95 million, that is 8.5 times increases. The consumption has increased 6 times (Shinwari et al. 2003).

Moreover, even if Pakistan is endowed with rich medicinal herbal sources, that are used for aromatic and medicinal purposes, some plants are well studied while others are still under process. As a developing country, Pakistan needs to enhance the herbal research and its applications for medical purposes.

4 Threats to Medicinal Plants in Pakistan

Environmental and climatic changes greatly affect the life on earth. Pollution, deforestation, industrialization, and population growth are factors that globally cause the decline of natural resources in quantity and quality. As a consequence, many plant and animal species are at the risk of extinction. The efforts to conserve natural flora and fauna through national parks, by providing natural habitats to wild organisms, are effective at the zonal level.

In Pakistan, 10% of the medicinal flora has been reported by Shinwari et al. (2000) two decades ago to be endangered species due to many factors such as poverty, population growth, and the lack of social institutions, planned cultivation, and interest and awareness about raising medicinal plants. Urbanization, rapid construction of roads, industry, pollution, and industrial farming are also important factors threatening natural medicinal resources. Moreover, the increased demand for land to meet the needs of livestock, timber, fuel wood, and fodder causes deforestation. With the decline of forests, the habitat of herbal plants is also decreasing (Saxena et al. 2001). In the same vein, the country gives shelter to thousands of Afghan refugees over many years despite being an over-populated country. This community is suffering from poverty and unemployment; thus, storing and sailing important plants are an alternative source of income.

In addition, the commercial collection of medicinal flora for consumption in the country causes an increasing danger to their sustainable availability (Gilani et al. 2009). Two major companies (Qarshi and Hamdard) produce herbal medicines and use wild flora extensively from all over the country. This situation causes the extinction of costly plants from wild flora and also increases the prices of related products. On the other hand, areas from which plants are collected are backward and the local populations are often unable to improve their livelihoods because the revenue generated from these plants is mostly at the benefit of a few persons.

In Pakistan, all medicinal plants are collected from wild resources. In most cases, those who collect such plants are unexpert and do not know the efficient way of collection. From the site of collection to national and international markets, each medicinal product or drug passes through many middlemen; this speculation often causes the increase of the cost and the final price manifold (Shinwari 2010).

5 Herbal Medicine Research in Pakistan

The local population of different zones have an indigenous knowledge about the medicinal uses of many plants, and this knowledge is often transferred from a generation to another (Bhardwaj and Gakhar 2005). However, when this knowledge is limited to a group or a person, it may be lost, hence the need to preserve it properly. The modernization and decline of traditional cultural values often cause the wastage of such a precious knowledge about medicinal plants (Martin 1995). Ethnobotany is the science of gathering and arranging the local indigenous knowledges about the conservation of medicinal herbs by local peoples for curing (Shenji 1994). It is highly required to transfer the essential ethnobotanical knowledge about herbs, which is disappearing very fast, to younger generations. This will make transmitted knowledge and data beneficial for future medicinal studies (Qureshi et al. 2001).

Herbal drugs are extensively used against various diseases. There is an abundant flora provided by nature for human and other living beings with several benefits (Bhatti et al. 2001). However, many plants are not explored yet and there is a need to find out their medicinal potential (Baquar 1989). Meanwhile, the harvesting of medicinal plants should be regulated, and there is an urgent need to conserve such plants and to reduce the harvesting rate according to the regeneration rate of each plant. In this perspective, Shinwari and Qaiser (2011) reported that local farmers and people of Pakistan marginally contribute to the conservation, rearing, and stability of medicinal plants.

Keeping in view the pivotal role of medicinal plants in our daily life, in case of direct use, indirect use, herbal medicine, and as by-products, it is highly needed to conserve the potential flora. Conservation strategies may be in situ and ex situ and should cover as well the cultivation process for a sustainable use of medicinal plant resources. Furthermore, plant breeding and genetical approaches should be utilized for the improvement of medicinal flora and proper long-term preservation of plant propagules in gene banks (seed bank, DNA libraries, etc.).

In Pakistan, the research on medicinal plants is very limited and often done by universities. However, advanced research in this area is still unconventional despite the fact that the country has a large diversity of medicinal herbs. Indeed, there are a few institutions where research and study of medicinal herbs are done and scientific laboratories and chemical analysis are still lacking. At present time, only traditional knowledge is transferred from generation to another with research projects undertaken in the country by some scientists. Some examples are presented below.

Baluchistan and northern areas of Pakistan are not only rich in medicinal flora, but also the center of origin and diversity of many Generas—e.g., *Cousinia*, *Allium*, and *Astragalus*. Some of them are near extinction, and the rest is explored and studied for medicinal purposes. There is a large diversity found in more than 13 Natural Regions from alpine to mangrove forests (Shinwari et al. 2003). They are alternative sources of cure; e.g., an active ingredient from peppers (*capsaicin*) is used as anti-pain without affecting other sensations (Binshtok et al. 2007). Malik et al. (1990) work in six districts of Baluchistan and gather useful information in the area of herbal medicine. Goodman and Ghafoor (1992) had done a comprehensive ethnobotanical survey in the areas of Baluchistan, gathering and studying 114 plant species used by local peoples as herbal medicine. Leporatti and Lattanzi (1994) undertook their study in the region of Makran and focused on 27 important plants by reference to their ethnomedicinal potential. Qureshi and Bhatti (2007) stated the effective uses of wild gourd (*Citrullus colocynthis*) from Nara Desert, Sindh, while demonstrating its taxonomic traits and medicinal uses. Qureshi and Bhatti (2008) reported as well, by reference to the same study area (Nara Desert, Sindh), 51 plant spp. from 43 genera and 28 families used by local peoples for medicinal purposes. They also explored 21 species that are not recorded in the Indo-Pak medicinal history.

6 Protection of Herbal Medicines: Recommended Measures

To conserve the medicinal flora, the control of access to plant resources and the plant protection are to be planned with long-term effects. For a practical implementation of the management strategy, a comprehensive knowledge about the ecological parameters and socio-economic trends is required.

Although the profession of pharmacy in Pakistan is steadily advancing, the country's healthcare system has to recognize the pharmacist's role in the cure. This lacking recognition is due to the limited interaction among pharmacists and customers. In Pakistan, pharmacists are concerned with their professional role and they do not think about the future prospects of the healthcare system. Moreover, there is a shortage of pharmacists in pharmacies. They are concentrated on management more than customers. Thus, the pharmacist's role is not familiar with the public needs as a healthcare professional. By enhancing both the knowledge and the collection of local nursery-based stocks, a substantial reduction of pressure on wild medicinal plants may be achieved. The knowledge about the cultivation and growing of medicinal plants is not reaching farmers in effective ways, so that they can understand easily who actually utilize it practically. Then, the focus must be on the larger use of ex situ management and on the growing and establishment of nurseries with the aim to conserve important plants. Within a range of climatic zones, it is necessary to select ideal sites for the establishment of nurseries. The main criteria for the selection of species to be studied are the degree of extinction in the wild, the economic importance, and the availability of information about them. Sophisticated harvesting of medicinal plants, training of collectors, expertise in nursery techniques, and skipping middlemen between producers and consumers throughout the trading process are essential measures to be implemented.

There is currently an urgent need to develop rules about the collection and conservation of endangered species. These steps are necessary for the best use and conservation of a threatened diversity to avoid the depletion of such precious natural resources. Unfortunately, there is currently no management structure in Pakistan with relation to the area of medicinal plants.

7 Conclusion

Wild medicinal plants are an essential source of medicine in traditional systems. They are used as curing agents for human and animal health from times immemorial (Sher et al. 2000). Even in recent times, they keep their importance with similar uses as in the past. Many plants from forests and mountains are collected from the northern areas of Pakistan and Rawalpindi and are used as a cure of different health problems (Arshad and Akram 1999; Khan 1985, 1991). Herbal medicine has a well-established market, which facilitates the import and export of targeted plants.

10% of the known plant species is used to cure human and animal diseases. In Pakistan, a large population depend on such plants as medicines and source of income. These plants are wild, and some are cultivated like field crops. Children and women play important roles in collection and processing, and the livelihood of a large part of the population depends on these plants. The marketing of medicinal plants is handled by the local (Pansar) system.

Some important species are endangered in Pakistan due to many factors, including the over-collection by drug smugglers and the lack of conservation programs and a proper maintenance system. This is a gateway for interested researchers, businesses, and decision makers to plan research and action programs aiming at the production and conservation of medicinal plants with the objective of boosting income generation, especially for poor collectors and farmers.

References

Ali H, Qaisar M (2009) The ethnobotany of Chitral valley, Pakistan with particular reference to medicinal plants. Pak J Bot 41(4):2009–2041

Arshad M, Akram S (1999) Medicinal plants of University of Arid agriculture Rawalpindi. Hamdard Med. 40(3):46–50

Baquar SR (1989) Medicinal and poisonous plants of Karachi, Pakistan. pp 95–96, 184–185, 248–241, 337–440

Bhardwaj S, Gakhar SK (2005) Ethnomedicinal plants used by the tribals of Mizoram to cure cut and wound. Indian J Tradit Knowl 4(1):75–80

Bhatti GR, Qureshi R, Shah M (2001) Ethnobotany of Qadanwari of Nara Desert. Pak J Bot 33(special issue):801–812

Binshtok AM, Bean BP, Woolf CJ (2007) Inhibition of nociceptors by TRPV1-mediated entry of impermeant sodium channel blockers. Nature 449(7162):607–611

Elisabetsky E, Castilhos ZC (1990) Plants used as analgesics by Amazonian cabocols. Int J Crude Drug Res 28:309–320

Gilani SA, Kikuchi A, Watanabe KN (2009) Genetic variation within and among fragmented populations of endangered medicinal plant, Withania coagulans (Solanaceae) from Pakistan and its implications for conservation. Afr J Biotech 8:2948–2958

Goodman SM, Ghafoor A (1992) The ethnobotany of southern Baluchistan, Pakistan, with particular reference to medicinal plants. Fieldiance Bot 31(4):1–84

Hamayun M, Khan SA, Kim HY, Leechae IJ (2006) Traditional knowledge and ex-situ conservation of some threatened medicinal plants of Swat Kohistan. Pak J Bot 2(2):205–209

Haq I, Hussein Z (1993) Medicinal plants of Manshera District, NWFP Pakistan. Hamd Med 34(3):63–69
Khan M (1985) Report of participatory rural appraisal on agriculture at Bayun, Kalam, Swat. A Joint Pak/Swiss-Govt venture, pp 11–20
Khan AA (1991) Marketing of herbal drugs and its problems. In: Proceedings of the national workshop on appropriate use of medicinal plants in traditional medicine, NIH, Islamabad, pp 69–72
Kirba SS, Zengin F, Kursat M (2009) Antimicrobial activities of extracts of some plants. Pak J Bot 41(4):2067–2070
Leporatti ML, Lattanzi E (1994) Traditional phytotherapy on coastal area of Makran (Southern Pakistan). Fitoterapia 65(2):157–161
Malik SM, Shan M, Marwat Q (1990) Ecotaxonomical evaluation of valuable plants of Balochistan, Pakistan. Project Rep. No. 123. Pakistan Science Foundation, Islamabad
Martin GJ (1995) Ethnobotany: a people and plants conservation manual. Clapham & Hall, London, New York, Tokyo
Qureshi R, Bhatti GR (2007) Wild gourd: a green medicine. Hamdard Medicus 50(1):156–162
Qureshi R, Bhatti GR (2008) Ethnobotany of plants used by the Thari people of Nara Desert, Pakistan. Fitoterapia 79:468–473
Qureshi R, Bhatti GR, Shah M (2001) Ethnomedicinal properties of Aloe barbadensis Mill with particular reference to the people of Nara Desert. Hamdard Medicus 44(3):46–50
Saxena KG, Rao KS, Sen KK, Maikhuri RK, Semwal RL (2001) Integrated natural resource management: approaches and lessons from the Himalaya. Conserv Ecol 5(2):14 [online]. http://www.consecol.org/vol5/iss2/art14/
Shenji P (1994) Himalayan biodiversity conservation strategies. Himavikes Pub. No.3
Sher H, Ahmad M, Iqbal CM (2000) Market survey of medicinal plants in major cities of Pakistan, their use and future prospects. Swiss Purled, Development Cooperation, Berne, Switzerland, pp 33–47
Shinwari ZK, Gilani SS, Kohjoma K, Nakaike T (2000) Status of medicinal plants in Pakistani Hindukush Himalayas. In: Proceedings of Nepal—Japan joint symposium on conservation and utilization of Himalayan Medical Resource, pp 257–264
Shinwari ZK, Khan AA, Nakaike T (2003) Medicinal and other useful plants of district Swat-Pakistan. WWF-Pakistan
Shinwari ZK (2010) Medicinal plants research in Pakistan. J Med Plants Res 4(3):161–176
Shinwari ZK, Qaiser M (2011) Efforts on conservation and sustainable use of medicinal plants of Pakistan. Pak J Bot 43:5–10
Stewart RR (1972) An annotated catalogue of the vascular plants of west Pakistan and Kashmir. Fakhri Press, Karachi, p 102

Dr. Ijaz Rasool Noorka is Professor and Chairman at the Department of Plant Breeding & Genetics, Manager Research Operations & Farms and diversified administrative assignments at Ghazi University, Dera Ghazi Khan Pakistan. Prior to this,he served in Government of Punjab agriculture sector in multiple positions and University of Sargodha as Principal, Director Public Relations & Publications, Chairman PBG and member Syndicate. Prof. Noorka received an early education from countryside school of District Jhang, Pakistan and lastly the Post-Doctorate from the United Kingdom (UK). He was honored with Roll of Honor (Twice), University Color (Thrice). He is recognized as international scientist, innovative thinker with practical solutions-oriented outlook. Prof. Noorka was invited to represent his research findings throughout the globe, particularly in FAO (United Nation). Japan, China, Morocco, Iran, Turkey, Egypt, South Africa, India, Abu Dhabi (Twice), Saudia (Thrice), Sri Lanka, Italy, France, Singapore, Malaysia, Sudan, Dubai (Thrice), United Kingdom etc. His credit includes, international player, project collaborator

(University-Industry linkage programs), radio, TV anchorperson, having, 250 National & International publications and thirteen book chapters mostly published by Springer and CRC Taylor and Francis.

Dr. Mohamed Behnassi is a Full Professor and Head of Public Law in French Department at the College of Law, Economics, and Social Sciences of Agadir, Ibn Zohr University, Morocco. He is a Senior Researcher of international law and politics of environment and human security. He holds a Ph.D. in International Environmental Law and Governance (2003), a MSc. in Political Sciences (1997), and a B.A. of Administration (1995) from Hassan II University of Casablanca. He obtained a Diploma in International Environmental Law and Diplomacy from the University of Eastern Finland and UNEP, 2015. He is also an Alumnus of the International Visitors Leadership Program of the Department of State, United States of America. Dr. Behnassi is currently the Founding Director of the Center for Environment, Human Security and Governance (CERES). From 2015 to 2018, he was the Director of the Research Laboratory for Territorial Governance, Human Security and Sustainability (LAGOS). Recently, he was appointed as Expert Evaluator for the National Center for Scientific and Technical Research (CNRST/Morocco), and selected twice (2019-2024) as an Assessment Scoping Expert and a Review Editor by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and Member of the Mediterranean Experts on Climate and Environmental Change (MEDECC). He was also selected by The Intergovernmental Panel on Climate Change (IPCC) as Expert Reviewer of the 1st Order Draft of the Synthesis Report (SYR) of the IPCC VI Assessment Report (AR6). Accordingly, he was among the Lead Authors of the 1st Assessment Report (MAR1): *Climate and Environmental Change in the Mediterranean Basin - Current Situation and Risks for the Future* (MEDECC, 2021). Dr. Behnassi has published considerable number of scientific papers and book chapters in addition to 20 books, including recent ones on: *Food Security and Climate-Climate Smart Food Systems - Building Resilience for the Global South* (Springer, 2022); *The Climate-Conflict-Migration Nexus from a Human Security Perspective* (Springer, 2022); and Social-Ecological Systems in the Era of Risks and Insecurity - Pathways to Viability and Resilience (Springer, 2021). Dr. Behnassi serves as a reviewer for many global publishers (such as Routledge and Springer) and scientific journals with high impact factor. He has organized many international conferences covering the above research areas, managed many research and expertise projects, and is regularly requested to provide scientific expertise nationally and internationally. Other professional activities include social compliance auditing and consultancy by monitoring human rights at work and the sustainability of the global supply chain.

Dr. Zafar Iqbal Khan is a Professor of Botany in the Department of Botany, University of Sargodha. He is HEC Approved Ph.D. Supervisor and registered as the Productive Scientist of Pakistan for the year 2008 by the Pakistan Council for Science and Technology. He published more than 280 research articles in reputed national and international journals by securing impact factor >350. The main area of his research is the bioavailability of toxic and trace metals in soils to crops, animals, and humans, considering all of the properties of soils that modify this bioavailability. Ultimately, this research project has several goals, including the protection of food crops from toxic metal contaminants, the minimization of trace element deficiencies, and the development of methods for testing and remediating contaminated soils.

Mr. Hafeez-Ul-Hassan is the final year student of M.Sc. (Hons) on Plant Breeding and Genetics, Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Pakistan.

Mr. Emran Manzoor is the final year student of M.Sc. (Hons) on Plant Breeding and Genetics, Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Pakistan.

Mr. Syed Shujat Ali is the final year student of M.Sc. (Hons) on Plant Breeding and Genetics, Department of Plant Breeding and Genetics, College of Agriculture, University of Sargodha, Pakistan.

Fostering Health Security Through Biodiversity: A Case Study from Ogun and Lagos States, Nigeria

Oluwakemi Osunderu

Abstract Over three-quarters of the world's population is using herbal medicines with an increasing trend globally. Herbal medicines are beneficial because medicinal plants are used to address the twin challenge of promoting sustainable livelihoods and treating numerous illnesses in Nigeria. However, in a recent study conducted among Traditional Medicine Practitioners (TMPs) in Ogun and Lagos States, Southwest Nigeria, it was confirmed that there are signs that the impacts of climate change are already being felt, not only in terms of increase in temperature, but also in respect of the availability of medicinal plants for the treatment of diseases in the forest zone of Nigeria where these states are located. Based on this, the aim of the study is to provide a better understanding of how TMPs contribute to the social, economic, and political problems posed by climate change in Africa and to identify the processes, methods, and tools which may help Africans at the grassroots adapt and make positive contribution to mitigate the effects of climate change. Snowball sampling method was used to identify the respondents, and data was collected using in-depth/structured interviews and review of secondary data. As outcome of this work, some developed tools may be used to encourage and guide specific actions to adapt to changing climatic conditions. In addition, it was possible to outline some steps which may be taken in order to create a more systematic method of adaptation strategies by organizations and people interested in the different levels of responses given to climate change induced threats in Nigeria and Africa.

Keywords Climate change · Diseases · Forest · Herbal medicines · Traditional medicine practitioners (TMPs)

O. Osunderu (✉)
Forestry Research Institute of Nigeria (FRIN), Ibadan, Nigeria
e-mail: osunderu.oluwakemi@frin.gov.ng; oaoluwakemi@gmail.com

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_14

1 Introduction

Biodiversity provides, among others, numerous ecosystem services, and most of them are crucial to human well-being at present and in the future. The application of ecosystem services and goods to the well-being of Nigerians is extensive, and it cuts across the population with chronic illnesses such as epilepsy (Danesi and Adetunji 1994), hypertension (Amira and Okubadejo (2007), diabetes mellitus (Ogbera et al. 2010), and other diseases. Nigeria's health sector is currently facing many challenges ranging from inadequate human resources, incessant trade union disputes, in addition to the issues of Universal Health Coverage. Biodiversity has the potential to strengthen the primary healthcare system if it can be fully integrated into disease treatment protocols in Nigeria (Soladoye et al. 2013). The medicinal plant industry is part of an international health industry of huge economic scope and has the potential for considerable development (WHO 2006).

Farnsworth (1988) concluded that most vulnerable medicinal plant species in Africa are popular slow reproducing species with specific habitat requirements and limited distributions. These characteristics made it imperative to promote medicinal plant cultivation based on market demand because it is difficult for medicinal plants to become commercially significant. A species needs to be very special in order to join the relatively elite club of important commercial plants. Fortunately, with enough background information, there is increased hope of profitably growing medicinal plants in Nigeria.

The government and landholding communities are not able to reverse the devastating state of the natural forests; the land available for in situ conservation is being reduced on an annual basis for alternative uses such as agriculture and public infrastructure. For example, about 4535 km^2 of protected forests were de-reserved for the purposes of agricultural production between 1960 and 2020 (Osemeobo 2010; Ehiagbonare 2010; Orji 2020). These unplanned land use practices weakened the ability of the forests to withstand the pressures of sustaining trade in medicinal plants.

2 Results and Discussion

Thirty-eight species of medicinal plants were identified from the information supplied by the TMPs. Table 1 shows the distribution of the species in relation to the source, status, parts of the plant used, and availability within the study area.

The life forms of these plants (Table 1) show that the trees constituted the highest number (66%), followed by shrubs (20%), herbs (11%), and rhizomes (3%). In all, the family *Leguminosae* was dominant with 4 species. This was followed by *Annonaceae*, *Anacardiaceae Euphorbiaceae*, and *Caesalpinioideae* (3 species each). The existence of other plant families in Table 1 demonstrates the rich forest biodiversity in Southwest Nigeria. This also shows the dynamism in ecosystem maintenance. A number of these are also used for economic purposes and are consumed as food in

Table 1 Availability of medicinal plants used for the treatment of diseases in Southwestern Nigeria

S/No	*Species*	Family	Floral Type	Source	Status of availability	Parts used
1	*Annona senegalensis Pers*	Annonaceae	Shrub	Free areas, forest	Abundant	Fruit, Leaves
2	*Khaya ivorensis* A. Chev	Meliaceae	Tree	Free areas	Rare	Stem, Branches Bark
3	*Magnifera indica*Linn	Anacardiaceae	Fruit Tree	Free areas, forest, plantation	Abundant	Leaves, fruits, bark, branches, stem
4	*Anacardium occidentalis* Linn	Anacardiaceae	Fruit Tree	Free areas, farmland, forest, plantation	Abundant	Fruits, branches, stem
5	*Spondias mombin* Linn	Anacardiaceae	Fruit Tree	Farmland, free areas, forest	Scarce	Fruits, bark
6	*Xylopia aethiopica (Dunal) A. Rich*	Annonaceae	Tree	Free areas,	Abundant	Leaves branches
7	*Alstonia boonei* De Wild	Apocynaceae	Tree	Free areas, forest	Scarce	Leaves, bark, root
8	*Citrus medica* Linn	Rutaceae	Shrub	Free areas, forest	Abundant	Leaves
9	*Morinda lucida* Benth	Rubiaceae	Tree	Free areas, forest	Abundant	Leaves
10	*Vitex doniana* Sweet	Verbenaceae	Tree	Free areas, forest	Abundant	Fruit, leaves
11	*Enantia chlorantha* Olive	Annonaceae	Tree	Free areas, forest	Scarce	Bark
12	*Piliostigma thinning* Milne Redhead	Leguminosae Sub: Mimosoideae	Shrub	Free areas, forest	Abundant	Leaves
13	*Ricinodendron heudelotii*(Baill) Heckel	Euphorbiaceae	Tree	Free areas, forest	Scarce	Leaves, bark
14	*Ficus sur* Forssk	Moraceae	Tree	Free areas, forest	Abundant	Fruit, bark
15	*Margaritaria discoidea*(Baill.) Webster	Euphorbiaceae	Tree	Free areas, forest, dry outliers	Scarce	Leaves, branches, stem, bark, roots

(continued)

Table 1 (continued)

S/No	*Species*	Family	Floral Type	Source	Status of availability	Parts used
16	*Azadirachta indica* A. Juss	Meliaceae	Tree	Free areas, plantation	Abundant	Leaves, branches, stem
17	*Aframomum melegueta* Lindl	Zingiberaceae	Shrub	Free areas, forest	Abundant	Fruits
18	*Terminalia catappa* Linn	Combretaceae	Tree	Free areas, forest	Abundant	Leaves, fruit, branches, stem
19	*Afzelia africana (*Smith) Sm	Leguminosae Sub: Caesalpinioideae	Tree	Forest area, forest	Abundant	Branches, stem, bark, root
20	*Erythrophleum suaveolens*(Gull. and Perr.)	Leguminosae Sub: Caesalpinioideae	Tree	Forest	Rare	Leaves, branches, stem, bark, root
21	*Rauwolfia vomitria* A fzel	Apocynaceae	Tree	Free areas, forest	Abundant	Leaves, fruit, bark, root
22	*Cordia millenii* Bak	Bignoniaceae	Tree	Free areas, forest	Scarce	Leaves, branches, stem
23	*Vernonia amygdalina*(Schreb) Del	Asteraceae	Tree	Free areas, forest	Abundant	Leaves, branches, bark, root
24	*Elaeis guinensis* G. Don	Palmae	Palm Tree	Swampy areas, forest,	Abundant	Frond, exudate, bark
25	*Daniellia oliveri* Rolfe	Leguminosae Sub: Caesalpinioideae	Tree	Savannah forest, re-growth	Abundant	Branches, stem, bark, root
26	*Zingiber officinale* Rosea	Zingiberaceae	Herb	Free areas, forest	Abundant	Rhizome
27	*Distemonanthus benthamianus* Benth	Leguminosae Sub: Caesalpinioideae	Tree	Forest	Abundant	Leaves, branches, stem, bark, root
28	*Sida acuta*	Malvaceae	Herb	Forest\wild, cultivate	Abundant	Leaves, branches, stem, root
29	*Mirabilis nyctaginea*	Nyctaginaceae	Herb	Forest\wild, cultivate	Abundant	Leaves, branches, stem, root

(continued)

Table 1 (continued)

S/No	*Species*	Family	Floral Type	Source	Status of availability	Parts used
30	*Zanthoxylum zanthoxyloides*	Rutaceae	Herb	Forest\wild, cultivate	Abundant	Branches, stem, bark, root
31	*Ageratum conyzoides*	Compositae	Shrub	Wild	Abundant	Leaves, branches, stem, root
32	*Allium sativum Linn*	Liliaceae	Rhizome	Forest\wild, cultivate	Abundant	root
33	*Helianthus annuus*	Asteraceae	Shrub	Forest/wild, cultivate	Abundant	Leaves
34	*Securinega virosa*	Euphorbiaceae	Shrub	Forest\wild, cultivate	Abundant	Leaves, stem,
35	*Vitellaria paradoxa*	Sapotaceae	Tree	Forest\wild, cultivate	Abundant	Leaves, stems, root
36	*Saccharum officinarum Piper*	Poaceae	Shrub	Forest/wild, cultivate	Abundant	Fruit
37	*guineensis*	Piperaceae	Shrub	Forest\wild, cultivate	Abundant	Leaves, stems, roots
38	*Garcinia koli*	Guttiferae	Tree	Forest\wild, cultivate	Abundant	Leaves, stems, roots, fruits

one way or the other (Malik 1998). Some of these include *Anacardium occidentalis, A*, *Mangifera indica*, *Musa sapientum, Citrus medica,* and *Vernonia amygdalina.*

The majority of the TMPs source their medicinal plants from free areas and rarely cultivate them. Table 1 also shows that some of the plants are already scarce and species regeneration is mainly ensured through growing in the wild. Gbile et al. (1981) and Oguntala et al. (1996) reported that Nigerian ecosystems are at greater risk of extinction if urgent attention is not given to the cultivation of medicinal plants. Table 1 shows that 90% of the TMPs use the whole plant for treatment which means that they make use of the fruits, stems, barks, and leaves at the same time. Table 1 also shows that the forest products used for the treatment of diseases are multipurpose; they are used as firewood, medicine, foods, chewing sticks, and animal feeds (*Ageratum conyzoides*). This corroborates the works of Adekunle (2001).

The results identified seven species belonging to seven different families: *Rutaceae, Asteraceae, Anacardiaceae, Annonaceae, Meliaceae, Guttiferae,* and *Leguminaceae* topping the TMPs priority list. The list of plants used by TMPs is in consonant with earlier research done by Adekunle (2001) and Olapade (2002), who have reported extensive use of plants in Southwest Nigeria. The supply of medicinal plants and other forest products has immensely contributed to the traditional health care and income of stakeholders in this sector. The availability of medicinal plants and particularly the ability to choose among many species for medical preparations have been a determining factor of the prices of traditional healthcare delivery.

Forest products explored in the study area were mainly wild stocks where the species occur naturally in the forest. This has resulted into special investment problems with medicinal plants because most medicinally important species that might seem worth developing as new crops are undomesticated. These often have a limited yield, mature irregularly, are very variable, are not suited to current planting and harvesting machinery, or present many other problems such as seeds are often difficult to obtain; expertise and knowledge are often in very short supply (and often are regarded as trade secrets); plant breeding and silviculture have become necessary; management techniques will have to be developed; and markets will have to be located or developed.

Economic analysis showed minimal competition in the forest product market and a high level of monopoly with a Gini coefficient of 0.83. Net profit realized by the TMPs was N650, 769.98 per annum while the rate of return was 280.08%. The traditional medicine enterprise is making a huge contribution to the GDP of Nigeria while contributing its quota to the per capita income and the standard of living of Nigerians.

The application of ecosystem services and goods to the well-being of Nigerians is extensive although traditional agriculture in Nigeria is having difficulties, and there is a great need for initiative that involves new crops and new products. Medicinal plants are mostly obtained in rural settings—both from wild plants and from plants cultivated on small farms—therefore, there is a need for governmental initiatives that encourage rural development in a sustainable fashion. Private sector interest alone is often insufficient to initiate or expand projects such as the proposed medicinal plant initiative, and government funding is needed as a catalyst.

3 Conclusions and Recommendations

The appropriate use of ecosystem services and goods in health care will help mitigate many food and health security challenges, thus facilitating the achievement of Sustainable Development Goals (SDGs) related to health and environment.

The outcome of this work has further supported the fact that over three-quarters of the world’s population are patronizing ecosystem services and goods for health care (Fakeye et al. 2009) with an increasing trend globally. Medicines may be beneficial but are not completely harmless (Oshikoya et al. 2008).

The following recommendations are given as outcome of the present study:

- The study shows that the biodiversity resource market in Nigeria is monopolistic. It is dominated by a very few old but well-experienced players. Also, the regression analysis shows that age, educational status, and years of experience all contribute to the profits of the TMPs; therefore, the government should encourage the youth to engage in practice by providing an enabling environment such as education and incentives. More precisely, the government should put policies in place to encourage the youth to learn the practice by setting up ethno-forestry institutions. Incentives related to the protection of the intellectual propriety rights (IPR) of older TMPs, which will encourage them to share information, should be adopted as well. Accordingly, academics should be encouraged to put their healing knowledge into practice since they have gathered information on the healing properties of forest products over the years.

- The forests should not be harvested beyond their annual yields in order to prevent the devastation of the resource base. The forests where medicinal plants are harvested are under traditional management regimes within the framework of common property utilization. Unfortunately, these natural forests lack planned conservation practices despite the huge quantity of medicinal plants harvested on annual basis. Poor forest management is largely due to poor funding, land tenure factors, lack of adequate research on the biology and ecology of species, and non-application of biotechnology to improve forest plants and meet market demands (FAO 2005).
- For the Nigerian Government to achieve SDGs related to health and environment, attention must be given to the role played by TMPs in the utilization of biodiversity resources for treatment and management of diseases.
- It should be made mandatory for all operators in the sector to declare the source of purchase of medicinal plants to the relevant authorities as this will help in biodiversity conservation. It will also help the legalization of production contracts, thereby protecting the interests of primary producers.
- There should be the standardization of morphological/biochemical methods to identify the medicinal plants and uniform method to analyze the effect of cultivated species on drug quality.
- Governments at all levels should support investment in the medicinal plant industry with particular regard to the establishment of cooperative producer/processor/retailer networks.
- Each forestry department can establish herbal research unit for drug production research, teaching, and training. Traditional medicine practitioners should be allowed to offer consultation in our general hospitals alongside the orthodox doctors so that the patient has a wide choice of healthcare services; this practice is already used in other countries such as Ghana.
- The time has come for economic and financial policymakers, the international financial community, and/or international domestic investors to start large-scale cultivation of medicinal plants, especially those with proven efficacy and safety. Most of these plants grow well even on deteriorating soil.

References

Adekunle AA (2001) Ethnobotanical studies of some medicinal plants from Lagos State, Nigeria. Niger J Bot

Amira CO, Okubadejo NU (2007) Frequency of complementary and alternative medicine utilization in hypertensive patients attending an urban tertiary care centre in Nigeria. BMC Complement Altern Med 7:30. https://doi.org/10.1186/1472-6882-7-30

Danesi MA, Adetunji JB (1994) Use of alternative medicine by patients with epilepsy: a survey of 265 epileptic patients in a developing country. Epilepsia 35:344–351. https://doi.org/10.1111/j.1528-1157.1994.tb02442.x

Ehiagbonare J (2010). Forest regeneration, dereservation and management in Edo State, Nigeria. African journal of biotechnology 7(25).

Farnsworth NR (1988) Screening plants for new medicines. In: Wilson O (ed) Biodiversity. DC; National Academy Press, Washington, pp 83–97

Fakeye TO, Adisa R, Musa IE (2009) Attitude and use of herbal medicines among pregnant women in Nigeria. BMC Complement Altern Med 9:53. https://doi.org/10.1186/1472-6882-9-53

FAO (2005) The support role: the use of forest resources in other production sectors. World Bank Publication, 2004–2005

Gbile ZO, Ola-Adams BA, Soladoye MO (1981) Endangered species of the Nigerian flora. Niger J For 8:14–20

Ogbera AO, Dada O, Adeyeye F, Jewo PI (2010) Complementary and alternative medicine use in diabetes mellitus. West Afr J Med 29:158–162

Oguntala AB, Soladoye MO, Ugbogu OA, Fasola TR (1996) A review of endangered tree species of cross river state and environs. In: Proceedings of the workshop on rain forest of South Eastern Nigeria and South Western Cameroon, Oct 20–24, 1996, Calabar, Nigeria, pp 120–125

Olapade EO (2002) The herbs for good health. The 50th Anniversary Lecture of University of Ibadan. Nature cureseries. Vol 3, 230p

Orji S (2020) Takeover of Nigerian reserve highlights uphill battle to save.news.monogabay.com

Osagie AU, Eka OU (1998) Nutritional qualities of plant foods. Ambik Publishers, Benin City, p 245p

Osemeobo GJ (2010) Can the rain forests of Nigeria sustain trade in medicinal plants? Int J Soc Forest (IJSF) 3(1):66–80

Oshikoya KA, Senbanjo IO, Njokanma OF, Soipe A (2008) Use of complementary and alternative medicines for children with chronic health conditions in Lagos Nigeria. BMC Complement Alterne Med 8:66. https://doi.org/10.1186/1472-6882-8-66

Soladoye MO, Ikotun T, Chukwuma C, Ariwaodo J, Ibhanesebor GA, Agbo-Adediran OA, Owolabi SM (2013) Our plants, our heritage: preliminary survey of some medicinal plant species of South-western University Nigeria Campus, Ogun State Nigeria. Ann Biol Res 4:27–34

World Health Organization (2006) WHO report on traditional medicine, my documents/WHO traditional medicine

Oluwakemi Osunderu is an Alumna of the United Nations University and a seasoned ecosystems health practitioner with a 21-year experience. Trained on Implementation Research (IR), with a focus on Infectious Diseases of Poverty (IDP). Osunderu has a proven successful track record in One Health related researches and supporting public health research programmes at positions of increasing complexity and responsibility at the Nigeria Natural Medicine Development Agency (Federal Ministry of Science and Technology), the Federal College of Complementary and Alternative Medicine (Federal Ministry of Health), the National Open University of Nigeria, and the Forestry Research Institute of Nigeria (Federal Ministry of Environment).

Fostering the Sustainable Forest Management in Saudi Arabia from Resilience and Mitigation Perspectives

Loutfy El-Juhany, Irfan Ahmad, Mirza Barjees Baig, Muhammad Farrakh Nawaz, Muhammad Asif, Muhammad Haroon U. Rashid, and Mehak Shaheen

Abstract Globally, forest cover is shrinking and vanishing alarmingly. The overall health of forest ecosystems is also declining due to a wide range of biotic and abiotic factors. In the Kingdom of Saudi Arabia, many factors are influencing forest ecosystems, including the natural ones such as harsh environmental conditions due to high temperatures, overwhelming drought, and low and irregular pattern of rainfall. Additionally, many anthropogenic activities, such as land clearing for urban areas expansion, cultivation of agricultural crops, and cutting fuelwood, are making significant impacts. The interaction of both natural and anthropogenic dynamics is compounded by the lack of qualified and professional forestry personnel in comparison with the optimum required to implement planned activities and to ensure a sustainable forest resource management. In such a situation, it is important to manage such resources with reference to scientific inputs to ensure their long-term sustainability. For instance fostering the community's resilience in this area, through educational and awareness programs, is also essential. This chapter identifies the factors threatening the sustainability of forest resources and the challenges and issues facing their sustainable management while developing ways to address them. It concludes with a review of viable options and suitable strategies to assist and work with the potential consumers and users of such resources. The purpose is to present the critical analyses based on the available literature, so all stakeholders, including extension staff, foresters,

L. El-Juhany (✉) · M. B. Baig
Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riyadh, Saudi Arabia
e-mail: ljuhany@ksu.edu.sa; ljuhany@gmail.com

M. B. Baig
e-mail: mbbaig@ksu.edu.sa; drbaig2@yahoo.ca

I. Ahmad · M. F. Nawaz · M. Asif · M. H. U. Rashid
Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan

M. H. U. Rashid
College of Forestry, Fujian Province, Fujian Agriculture and Forestry University Fuzhou, Fuzhou 350002, PR China

M. Shaheen
Department of Forestry, Range and Wildlife, Ghazi University, Dera Ghazi Khan, Pakistan

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_15

policymakers, and planners, could help ensure the sustainability of forest ecosystems and fostering the resilience of communities to build their capacity in conserving the meager forest resources of the country.

Keywords Capacity building · Case studies · Climate change · Deforestation · Extension education · Forests of KSA · Participatory forest management · Sustainability

1 Introduction

The importance of forests is widely known due to their important environmental, social, and economic roles. Trees are known as natural filters of the environment. They are essential for the stabilization of land, the protection of watershed areas, as windbreaks, and the control of erosion and desertification. Moreover, in terms of fertility and restoration of soil and amelioration of microclimate change, the role of forests cannot be neglected. Furthermore, forests provide habitats for flora and fauna, and many tree species are also used for browsing household animals. Also, forests provide different goods and services and are a source of livelihoods to adjacent communities living near the forests (El-Juhany 2009).

The forest ecosystem stores carbon in different ways, mainly through forest vegetation carbon, soil carbon storage, and litter carbon storage (Hérault and Piponiot 2018). Forests act as global carbon sinks and store 283 Gt of carbon in its green biomass, 38 Gt in dead wood, and 317 Gt in upper 30 cm of soil layer and litterfall (Sanquetta et al. 2011). The forest ecosystem has a greater capacity of storing carbon contents, which is far more than the carbon present in the atmosphere. In 2005, it has been reported that forests store 638 Gt of carbon (Kaewkrom et al. 2011). This reported carbon is pooled with a gross uptake of carbon by Earth, which was assessed at 2.4 Gt a year, and most of this is sequestrated by forests (Joint Liaison Group of the Rio Conventions 2008).

Spreading over an area of about 2,149,690 km^2, Kingdom of Saudi Arabia (KSA) represents about four fifth of the Arab Peninsula. Geographically, KSA is divided into two major zones: the rain-fed zones of the western and southern highlands (Taif), in which natural forests are found, and the arid zone in the north (Al Nafie 2008), which consists of a variety of ecosystems, landscapes, and biodiversity, including wadis, mountains, valleys, meadows, volcanic mountain, and sand deserts (Fig. 1). These ecosystems present unique biodiversity of flora and fauna with wadis, mountains, and deserts as the principle topographic feature of KSA. In wadis, the vegetation cover is mainly composed of pastures and is a habitat to grazing communities. The arid areas of south-western highlands are characterized by distinct and temporarily formed desert wetlands, which are attributed to seasonal rainfall. These desert wetlands pose a particular challenge due to shortage of water, which is available only for short period of time after a heavy rainfall (Honke et al. 2019). The vegetation cover in these desert wetlands varies from aquatic in wet meadows to xerophytic species in

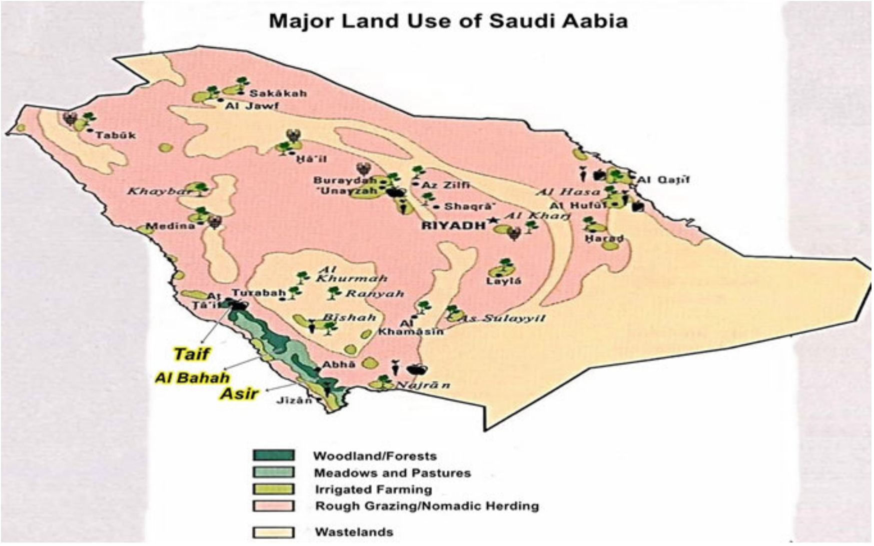


Fig. 1 Land-use pattern of KSA. *Source* GlobalSecurity.org

terraces of highlands depending on environmental conditions (Galal et al. 2021). According to FAO (2010), out of the total land cover, 977,000 ha of KSA consist of forest land, which is only 0.5% of the landmass; this makes the country a forest-deficient one. Out of a total area of 2.7 million km^2, 1.35% has been reported to sustain 2300 species of flora (Baig et al. 2019).

Forest vegetation having climax tree species and scattered shrubs in rangelands are present in the south-western semi-arid regions of KSA, which consists of Al-Sarawat Mountains covering an area of 1800 km (NCWCD and JICA 2006; El-Juhany 2015). These high mountains run parallel to the Red Sea. Generally, thin strands of weak and damaged forests are reported in these areas of KSA, mainly due to highly degraded lands, which are unable to support a healthy tree cover (El-Juhany 2015).

Many factors, like a harsh environment characterized by irregular pattern of rainfall, shortage of water leading to droughts, and extreme climatic conditions, represent a serious challenge to the forest vegetation. However, the negative impacts of climate change on forest ecosystems have not received so far the needed attention. Moreover, many anthropogenic factors, including the urban growth, agricultural practices, the industrial development, and forest clearing for fuelwood, have threatened the sustainability of forest ecosystems (Al-Subaiee et al. 2014). Indeed, many reports and research studies indicate that both the forestry sector and rangelands are under severe threat in different regions of KSA, and this is happening as a result of harsh environmental conditions—arid to semi-arid climate, poor soil, etc.—and anthropogenic activities—exploitation of forests, mismanagement of rangelands, and uncontrolled urbanization due to an exploding population. Most of the natural habitats in KSA, recognized as being in danger due to climate change, mainly consist of high hill forest and forest plantations, valleys, marshlands, and coastal belt.

Climate change is expected to have a devastating effect on the country's grazing and forest lands during the next five to ten decades, including an increase in the frequency and fluctuations of natural instabilities such as aridity, stormy winds, natural fires, and floods, as well as changes in species distribution, composition, and abundance that will lead to a decreased productivity and deforestation. Climate change will ultimately affect woodlands, rangelands, arable areas, fodder, and meat productivity. As a consequence, the socio-economic sustainability in countryside areas will be harshly stressed and rural migration is expected to increase radically.

Based on this background, the purpose of this chapter is to draw the attention of all stakeholders to the imperative need to identify and address the impacts, gauge the losses, conduct scientific studies on forest and rangeland degradation, and take remedial measures to combat environmental and climate risks.

2 Linkages Between Climate Change and Forests

People living at high altitudes or near forest spend their livelihood by mostly grazing their animals in forest or by cutting wood and selling wild fruits and nuts. Climate change has not only severely affected the grazing periods of livestock, but it has also affected the host–pathogen relationship by making some insect pests and fungi more thrived/powerful to attack, thus causing tree diseases and high mortality rate which led to CO_2 liberation causing more global warming. Generally, forests play an unparalleled role in mitigating the effects of climate change through carbon fixation. Shifting cultivation trend, industrialization, and urbanization of forests have led to the carbon discharge, which was meant to be removed by the forests. According to the Intergovernmental Panel on Climate Change (IPCC), deforestation caused by land-use modification accounts for 17% of global carbon emissions each year (Saikku et al. 2012). This carbon dioxide must be stored in forest area, which also protects biodiversity and provides ecosystem services.

Forest management covers best mitigation strategies with regard to climate change impacts and processes like hydrological cycle and albedo (Marland et al. 2003). Forests do demonstrate affiliation with the climate change in various ways:

- Degraded and cleared forests add about one-sixth of global emissions of carbon;
- Forests regulate ecosystems, protect biodiversity, and provide livelihoods to people;
- Forests react simultaneously in two ways with regard to climate change: first as a cause and second as emitter of greenhouse gases;
- Forests provide habitat to 80% of the world's terrestrial biodiversity;

- Forests absorbed one-third of the carbon dioxide which is emitted by burning fossil fuels, which approximately makes 2.6 billion tonnes of CO_2; and
- Carbon emissions expected for the first half of this century might be stored in their biomass, soils, and commodities.

As we know, forests react in a dual way, positive and negative, toward climate change with regard to CO_2. For instance, in some areas surplus amount of CO_2 may influence the fertilization of particular species by helping it grow better. In the same way, higher temperatures due to climate change can delay the growing season. Increased temperatures for prolonged times may provoke water stress, droughts, and spread of insect pests and pathogens, and ultimately, all these factors lead toward major forest dieback. Globally, forest ecosystems are facing widespread diebacks resulting in higher tree mortality rates. Fluctuating temperatures and drought spells have been found to be associated with such a decline and dieback. Seasonal droughts in tropical regions have further worsened the situation (Allen et al. 2010; Steinkamp and Hickler 2015).

There are intrinsic linkages between forests and climate change. Indeed, climate change is also the consequence of both forest decline and degradation. The first source of GHG emissions is fuel-based transportation, and, surprisingly, the second source includes forestry, agriculture, and other land-use sectors, which account for about a quarter of all global emissions. The latter can be controlled by providing best forest management. A strong message/pressure should be given globally to all communities to maintain their forest ecosystems, as it is the only cheapest source as compared to all other sources of lowering these emissions. If we only manage these forest ecosystems, the outcome will be surprisingly positive. The outcomes include reduction in greenhouse gas emission, the livelihood of people near forest community will improve, degraded forests and biodiversity will flourish, and by this, we can withstand climatic changes to some extent.

3 Forests Land in Al-Baha, Taif, and Asir Regions of KSA

It is located between 41° and 42° east longitude and 19° and 20° south latitude in the country's southwest in the Al-Baha region (Doha 2009). Mecca covers the northern and western boundaries of the city. Al-Baha lies between the Mecca and Asir regions (Fig. 2), and it is the tiniest of the country's 13 administrative regions, covering only 12,000 km^2 (Schulz and Whitney 1986; Saudi Geological Survey 2012). Due to its elevation above the sea level, the region has a mild temperature in summer and cool and wet winters. Moist breezes blow in from the narrow plains of Tihama in western KSA. The territory is split into two major sections by large and sharp Stony Mountains: 'Tihama,' the lowland coastline in the west, and 'Al-Sarat,' a hilly area at an altitudinal range of 1500–2450 m, covering certain areas of the Al-Sarawat Mountain ranges (Alahmed et al. 2010). Because of its green forests, wildlife regions, agricultural plains, valleys, and mountainous areas attract many tourists from KSA

Fig. 2 Map of the major forest lands of Saudi Arabia. *Source* ArcGIS Pro—Esri|Mapping Software

and the neighboring countries. Pleasant climatic qualities such as rainfall, suitable temperatures in summer and winter seasons, and foggy weather in the mountains have contributed to the region's status as a significant tourist destination (El-Juhany and Aref 2012a).

The forestlands of Taif are located between latitudes 20°00′ south and 21°36′ north and longitude 39°31′ west and 41°56′ east. These forests cover an approximate 24,428.60 km^2. Taif is located in the country's southwest region (Fig. 2), which has mountainous areas as well as some cropland lands. Taif's productive forests cover an area of 43.02 ha, with a total annual rainfall of no more than 500 mm (Abo-Hassan et al. 1984). Forests in the mountainous area are dominated by the climax species *Juniperus procera.* Some other important tree species include *Acacia gerrardii*, *Acacia origena*, *Ficus palmate*, *Ziziphus spina-christi,* etc., and shrubs and similarly some perennial herbs are also found (El-Juhany and Aref 2012b). Juniper trees in Taif, according to El-Juhany (2014), were between 56 and 132 years old and, on an average basis, about 83 years old. Taif woods have been utilized for a long time because of the visible consequences on the existing trees (El-Juhany and Aref 2013). These juniper forests are used for grazing, apiculture, and construction purposes. Local inhabitants living near these forestlands utilize forests to obtain fuel and construction wood. These woodlands support natural biodiversity and serve as home to different species of flora and fauna. Being a part of the worldwide forest vegetation, woodlands play a significant role in storing massive amounts of carbon in its biomass and soils. Forests in Taif are degrading due to the low natural regeneration aptitude of dominant and indigenous tree species, wide spacing between trees, a great proportion of infrequent trees, the disappearance of larger trees, eroded soils, tree dieback, and loss of wild animal species with a rise in monkeys. Deforestation and excessive grazing have both taken place in these woodlands. With this loss comes a reduction in forest soil's ability to hold water and support seed germination and growth. Using forest modeling as a starting point for future rehabilitation efforts could prove crucial and efficient (El-Juhany and Aref 2012a).

The Asir region covers a huge area, extending from the mountains' eastern slopes to the Empty Quarter's borders and from their western slopes to the Red Sea shore. Al-Sarawat Mountain range in the south-western KSA's Asir area occupies a large portion, with its northern boundary starting from the Baha area's southern border and ending at the border of northern Jazan areas as mentioned in Fig. 2 (El-Juhany and Aref 2013). In Asir and East Jazan, the trees are irregular, deteriorated, dieback-affected, and dead. Threats to the forests of this region include low natural regeneration capability of the principal forest species, tree diseases, forest fire spread, timber cutting, grazing, pest outbreaks, and recreational parks' growth (El-Juhany and Aref 2013).

Aref and El-Juhany (2000) reported that removing natural streams and infrastructure construction in south-western regions of KSA resulted in loss of environmental stability, which is also a main challenge faced by the forests of this region. Moreover, to a great extent, the forests had been overexploited by pests. The Asir region has a huge number of irregular trees (El-Osta 1983). Asir Mountains of juniper trees in Ridah Reserve were irregular and degraded (El-Juhany et al. 2008) due to the mechanical forces of wind, soil erosion, tree competition, and animal grazing. Apart from these anthropogenic activities, climatic effects triggering the drought are also contributing to forest decline in these regions (NCWCD 2005). Furthermore, according to Abo-Hassan et al. (1984), the comparatively high rainfall and deep soil in the Asir region ensured the juniper trees were vigorous and of superior value. Trees in Asir woods were more vigorous than those in Taif or Baha forests, according to the findings of El-Juhany and Aref (2013).

4 The Climate of KSA and Asir Region

With the exception of some regions in the western coast (Asir), most part of KSA falls in a desert climate. In general, the KSA consists of three climatic zones. The first zone is desert, which is almost everywhere. It is described by a very low rainfall and a very high day temperature, which drops at night. The average temperature in summers is 45 °C, which usually exceeds up to 54 °C from June to August. During winter, the temperature infrequently drops below 0 °C. However, a very low relative humidity combined with a high wind speed represents an important factor which makes the atmosphere cool. Another climatic zone is the Steppe along the western highlands, and the last zone consists of a small area of highlands with mild temperature and humid conditions, which results in long summers (WeatherOnline 2020). In summer, temperature of shady areas rises up to 38 °C in almost all part of the country.

The Indian Ocean monsoons have an impact on the high lands of KSA, which includes the region of Asir on the western coast. This time of year brings an average of 300 mm of rain, or roughly 60% of the cumulative average. However, in the rest of the country rainfall is rare and unpredictable. One or two large cloudbursts may account for the entire year's rainfall.[1]

The climate of the area fluctuates significantly depending on physiographic factors and season. The region's mountains receive variable rainfall in consequence of damp oceanic winds by south-western monsoon. Severe storms are triggered by these winds, which are elevated by the hills, and are most common in the spring and summer months. The average annual rainfall in the Escarpment Mountains ranges from 600 to 800 mm, with the dampest regions receiving more than 1000 mm. The high plateau obtains between 300 and 500 mm of rain per year, whereas the east gets less than 100 mm. It is possible to have frosts over 2000 m and snowfall on the highest mountains, but these situations are rare. Summer temperatures in the mountains range from 20 to 25 °C, while winter temperatures are around 10 °C (Miller 1994).

5 Climate Change Impacts in Central and West Asia

This region contributed least to global warming as it had a low carbon emission potential compared to most developed countries, but this ratio is now changing. This region is mainly vulnerable to climate change because of emissions generated somewhere else. As the temperature increases each passing year, it is also affecting human health. Heat waves, heatstroke, and heart attacks are becoming more frequent as a result of climate change. In Central and West Asia, the decline in rainfall is expected due to increasing temperatures in semi-arid and arid regions. These regions have huge populations, which mainly depend on their highly fertile lands. In addition, water resources are extensively used not only for agriculture, but also for energy production.

Most of the climate change events are predicted from rising temperatures and the increase of the carbon dioxide levels. The rise of Earth's temperature and the increase of GHG level in the atmosphere are currently supported by facts due to long-term measurements. Therefore, the effects of climate change on natural ecosystems are expected with various implications.

[1] Forecasts for 2020 are available (WeatherOnline 2020).

6 Forest Degradation Dynamics in KSA

6.1 Factors Affecting Juniperus Procera *Dieback in KSA*

Dieback can be caused by a variety of interrelated variables, which makes the prediction and cure of the disease very difficult (Ahmad et al. 2013; Ross 2013). There are several possible causes for the dieback and decline of forests, including exhaustive agricultural practices (i.e., overfertilization and overgrazing) and increased wildfires and climatic disturbances, especially droughts, floods, and extreme temperatures (Ahmad et al. 2016). Observation made by many researchers confirms the strong correlation between dieback and the spread of pest infestations. However, it is still not clear whether the dieback is induced by a disease, an organism, or perhaps a particularly warm summer. Generally, several gears are working at the same time against shrubs and trees for years (FAO 2009, 2007; Regent Honeyeater 2014).

According to El-Juhany et al. (2008), the dieback of *J. procera* trees has been spreading in the southwest forests of KSA for the past 35 years, although no single underlying cause has yet been discovered. Overgrazing, global warming, frequent droughts mixed with extended regeneration cycles, and a long-term rise in aridity are all factors behind the reduction of Arabian juniper woods (Fisher 1997). There are a number of key scientific questions associated with forest dieback. Also, there is no way to adequately simulate forest dieback in response to expected climate change, and the magnitude of climate stress that forests can bear until a massive dieback starts is still undetermined (Auclair et al. 2010). The dieback of juniper forests is potentially caused by the disease outbreak, water stress, anthropogenic activities, and climate change (Al-Hemaid 2007).

6.2 Mountainous and Grassland Ecosystems Under Stress

In addition to the consequences of global warming and drying, Central and West Asia's ecosystems are threatened by human activities, including pollution and overuse of natural resources. The delicate balance between the land, plants, and the people that rely on them is being disrupted as a result. The Central Asia's natural grassland coverage and grass yields are expected to fall by 10–30% by the mid-century. The changing environments can lead to an increase in the occurrence of some diseases, such as malaria in Tajikistan, which has seen a one-degree Celsius increase in average air temperature since the mid-1980s (Tolba and Saab 2009).

The Lebanon cedar and the Cilician fir have reached the southern point of their distribution in Lebanon, and their ranges will shrink as temperatures rise in the region. Climate change will also have a severe impact on KSA's juniper woodlands, which are presently confined to a limited region of around 7600 km^2 in size at extremely high altitudes varying from 2000 to 3000 m (National Report to the CBD). It has been observed that the juniper trees in the Jibal Ash-Sharah and Hijaz Mountains in southern Jordan and KSA are drying out at the tips, and the seed reproduction has diminished as a result of the reduced humidity and precipitation (Al-Eisawi 2012).

7 Forest Management and the Role of Local Populations

7.1 Saudi Arabians' Attitudes and Reliance on Natural Forests

Even though forests are vital natural resources and a major source of wood, their major ecological, economic, recreational, and eco-tourism advantages, as well as social advantages, make them extremely valuable (FAO 2011). Only 1% of KSA's land area is covered by forests (FAO 2011), which occupy an area of 27,280 km^2 (UN Statistics Division 2012). However, due to natural and anthropogenic causes, the country's forest resources are depleting and degrading at an alarming rate (El-Juhany 2009). Low rainfall, high temperatures, low humidity, and scarcity of rivers, as well as shortage of groundwater, all have a significant impact on the country's forest stands. These elements slow down forest regeneration, making afforestation and tree-planting schemes prohibitively expensive (Badai and Aldawoud 2004). Deforestation, degradation of natural grasslands, and the extension of agricultural land are considered now major impediments to the long-term development of KSA's forests (Ministry of Economy and Planning 2005; El-Juhany 2009). The country's Ministry of Agriculture has implemented a number of afforestation plans and projects to preserve, maintain, and develop the forest ecosystem.

There are diverse functions for forest extension, such as raising public knowledge about the value of forests, addressing concerns about the economic, social, and ecological benefits of forests, and demonstrating how these aspects are linked in urban and rural environments. Additionally, the forestry extension offers locals the chance to learn, contribute, and build skills and favorable attitudes toward forests through relevant education programs. These actions undoubtedly contribute to the preservation and improvement of the forest ecosystem and its resources. Indeed, the forestry extension can help shape the attitudes and behaviors of individuals and communities toward the forests they support (Agbogidi and Ofuoku 2009). According to earlier studies, projects in KSA had started with the goal of growing more trees, replanting forests, and getting more wood from existing trees. However, whether or not this approach can be successfully integrated into the forest management policies without the participation of the indigenous people has been debated. A comprehensive understanding of local people attitudes toward trees and the environment is critical in this process. The planners must have a comprehensive understanding of the local people, their socio-economic attributes, and their opinions regarding forests before introducing and implementing any management strategy in concerned regions (Agbogidi and Ofuoku 2009).

7.2 Local People's Attitudes Regarding Natural Forests Around Al-Baha Region

Overall, findings reveal that the population has a favorable opinion regarding forests. In order to promote tourism and encourage visitors to the Al-Baha area, trees play a crucial role (Al-Subaiee 2014). Studies have shown that forests may help the tourism business grow stronger, thus creating jobs and possibilities for the inhabitants (Table 1). People from arid and hot regions are brought to the Al-Baha region due to its hilly terrain, woods, warm climate, and visual attractiveness (NCWCD and JICA 2006). Communities in and around KSA's forests demand maximum resources for sustainable forest management (Al-Subaiee 2014). Participants were more concerned about their access to the resources, needed for forest expansion and their sustainability.

Additionally, people emphasized the need to prevent forest overgrazing and fires, considered by them as two issues which need to be addressed in forest management policies and interventions. According to the Ministry of Agriculture's (2002) report titled 'Forests National Work Plan and Strategy,' overgrazing has been identified as a serious hindrance to forest vegetation regeneration. Overgrazing causes trampling which degrades forests, thus triggering irregularities in forest vegetation such as dieback (Chaudhary 1997; Chaudhary and Le Houérou 2006).

They also found that the residents' support gave them the chance to get involved in projects linked to Al-Baha forest development and protection (Al-Subaiee 2014). Locals have shown a desire to step up and take on more responsibility in this regard. It has also been shown in numerous studies that the engagement and support of the communities are absolutely necessary if natural resources, especially forests, are to be preserved (Triguero-Mas et al. 2009). For the conservation of natural resources,

Table 1 Local's reliance on adjacent forests in Al-Baha

Purpose of dependence on forests	Without dependence on forests		Dependence on forests	
	Number	Percent	Number	Percent
Recreational activities and picnics	41	8.2	459	91.8
Fuelwood from the nearby forests	170	34	330	66.0
Grazing their livestock	254	50.8	256	49.2
Beekeeping	307	61.4	193	38.8
Timber for buildings	362	72.4	135	27.6

Source Al-Subaiee (2014)

particularly forests, several scholars have urged the use of collaborative methodologies and appropriate communication strategies (Sirivongs and Tsuchiya 2012). Macura et al. (2011) concur that transforming rights and responsibilities helps people in skill development needed for sustainable resources management. They argued for the establishment and implementation of a new forest management system that emphasizes extension education and training programs of people, as well as ensuring their participation in activities aimed at sustainable forest management.

8 The KSA's Climate Change Policy

Abdulkareem and Ellaboudy (2019) suggested that the 2018 climate change policy highlighted some issues of great importance. The major policy shift reflects the transition from a situation marked by reluctance of policymakers to address the dire effects of climate change on fragile ecosystems to their acceptance of climate risks and the willingness to invest in mitigation through renewable energy projects.

In February 2018, the Saudi government awarded ACWA Power a contract to build a 300-MW Sakaka IPP PV solar project in Al Jouf region, the first utility-scale renewable project in the country, which will cost \$300 million, create hundreds of jobs, and generate enough electricity to supply the power to roughly 40,000 homes. In March 2019, KSA and the SoftBank Group Corp. signed a memorandum of understanding to build the largest solar power development in the world at \$200 billion, thereby producing 200 GW and creating approximately 100,000 jobs. In September 2019, the government invited bidders to operate the new wind farm, Dumat Al Jandal near KSA's border with Jordan that will cost \$500 million and generate enough power to supply up to 70,000 Saudi households as it connects to the northern electricity grid.

Moreover, KSA has recently shown its willingness to invest in mega-renewable energy projects. Although it is known that the country is starting to shift toward more renewable energy, primarily in order to decrease its reliance on oil sales, it was understood that carbon emissions would also decrease as a result of shifting toward renewable energy sources (Abdulkareem and Ellaboudy 2019). The government is currently well aware of all climate change-related challenges and is increasingly ready to face them through comprehensive programs. The government has recently launched the Vision 2030 with major mitigation objectives. The country has also signed the Paris Agreement in 2016.

9 Sustainable Forest Management in KSA: The Need for a National Plan

The interaction of natural and anthropogenic activities remains the primary cause threatening the forest stands in KSA. There are several elements involved, but the lack of a forest management plan further complicates the issue of climate change. Local people used to take care of the country's woods under a traditional management system that exposed them to less difficulties than forests face currently. That practice was eventually abandoned in 1953, unfortunately (Assaeed and Al-Doss 2002).

9.1 The Need for Participatory Forestry Approaches and the Consideration of Indigenous Knowledge

Social and participatory forestry has gradually emerged as a viable forest management approach in several countries to ensure a long-term sustainability. Sustainable forest management requires the involvement, support, and cooperation of local populations. Different types of social forestry, comprising community forestry, agroforestry, farm forestry, and urban forestry, are being practiced worldwide (Tesfaye et al. 2012; Baig et al. 2019). Moreover, local communities are well-versed in forest management and may provide valuable contributions. Thus, they have a legal right to take part in related forestry activities. Local participation is essential for the interactive sustainable forest management to flourish (FAO 2016). Forest management concepts come from people who work closely with the woods and have direct knowledge and viewpoints on forest-related issues. Forest managers must be familiar with local populations and their fundamental socio-economic characteristics, needs, and knowledge in order to ensure a sustainable management of forests (Ozturk et al. 2010). According to Jewitt (1996), the government employees and forest periphery communities have been maintaining forests under various cost–benefit sharing agreements for many generations. This type of cooperative forest management method has achieved widespread acceptability for use around the world (FAO 2016). Indeed, this management approach is more effective and successful because it involves a variety of communities linked to forests that carry an abundant and rich knowledge on local woodlands, native experience-based expertise about the sustainable use of resources, and consented practices for access to adjacent forests (FAO 2016).

Therefore, the use of the rich indigenous people knowledge on forests should be increasingly promoted in the KSA. At present time, the Forest Department is still not utilizing this beneficial resource. Investigations by Al-Subaiee (2014) in KSA show that residents are keen to assist in the protection, preservation, and management of natural forests if they are allowed controlled access to forest commodities and services. Therefore, there is a need to investigate how local people may help improve sustainable forest management in the country. The current scenario is that forest resources in KSA are expected to be promoted, safeguarded, and conserved with the participation of local communities.

9.2 The Need for Climate Impact Assessment Studies in Forest Ecosystem

The forests in KSA, despite their limitation, are the most significant renewable natural resource, supporting a wide range of ecosystems, varying geographical features, and changing climates. Throughout the world, forests have long been recognized for their many environmental, economic, and social advantages. In order to define their significance and recognize their vital role in sustainable development, their productive and protective roles have been extensively addressed in international forums. There are several ways that forests can help protect the soil from wind and water erosion, the risk of flooding, and the damage to infrastructure caused by these natural disasters. Forests also play a critical role in reducing global warming by sequestering carbon dioxide and releasing oxygen into the environment. They also reduce KSA's dust and air pollution, both of which are serious environmental issues. The conservation of biodiversity (both flora and fauna), as well as environmental advantages, is among the critical functions of forests (Al-Subaiee 2014).

It is anticipated that climate change would not only decrease wood volumes in stressed environments, but all also have negative impacts on the above-mentioned benefits. Therefore, it is important to conduct scientific studies to gauge the impacts of climate change on the health of forest ecosystems and the services and goods they provide in every region.

The country's forests and rangelands are currently under risk because of the hot and dry environment. Mountain forests, valleys, meadows, wetlands, and coastal environments are all facing challenges due to climate change. However, future climate change impacts will have even more devastating consequences on rangelands and forests. The country's current natural disturbances could lead to increased dieback and die-off issues, disease spread, changes in species composition, lower productivity, and biodiversity loss in the forests (Gardner and Fisher 1994; FAO-RNE 2011). Gardner and Fisher (1994) mentioned that climate change can be considered responsible for juniper woodlands' inability to regenerate naturally, as well as the widespread presence of biological pressures. The hot, dry climate has proven to be a challenge for some native and exotic tree species, although this has not been the case worldwide. Plantations like this could help expand greenery, improve the microclimate and ecosystem, offer picnic places, reduce soil erosion, and provide habitats for some creatures and birds. KSA's woodlands, on the other hand, are in a bad condition as compared to those in adjacent countries.

10 Some Case Studies from KSA and Pakistan

10.1 Sustainable Forest Management and Tribal Protection System (TPS): A Case Study from KSA

A long time ago, people in the south-western region (covered with natural forests) of KSA found a suitable place to live where the prerequisites of life existed, including water as the most important one. Therefore, agricultural practices remained as the main source of livelihood for several generations. They knew its economic importance for their communities. This concern has evolved over time until it entered in tribal protection, which was applied to agricultural and non-agricultural activities later on. Aref and El-Juhany (2000) reviewed the historical tribal protection system (TPS) of the natural forests in the south-western region of the country as an early sustainable forest management plan. TPS included the members of the tribe to identify some areas around their farms, in which grazing at times of severe drought is not allowed as well as logging from the forests is owned by the tribe. Moreover, the contamination of water wells and streams was prohibited for all and the misuse or abuse of the natural environment in any way was also banned. So, applying the TPS resulted in a healthy environment, including less eroded soil with dense tree cover having an appropriate profile depth when compared with unprotected areas. In TPS, a group of five to ten persons chosen from each village or from the tribe assigned to apply the penalties stipulated in the agreement between members of the tribe to anyone who violates the protection system. Obedience to those members was obligatory for all members of the tribe. The texts of the protection systems may vary from a tribe to another, but the most common one among all the tribes was to ensure that forest trees are protected from felling, especially green ones, except where logging was allowed by a prior agreement between members of the tribe, but only in case of emergency.

Trees were evenly distributed, and the TPS has emphasized the prevention of grazing within forest lands to preserve new tree growth and keep the area protected for probably more than five years. In order to protect pastoral areas from degradation and encroachment, the group of men entrusted with the obligation to implement the protection system which encompasses the inspection of forest sites and grazing land. This is especially important at certain times of the year when grazing was prevented to maintain some pastoral sites for a period of time to encounter the lack of rain that may happen.

If any infringement being observed on a protected site, the aforementioned monitoring group can conduct an investigation within and around the village to monitor and punish offenders, often fined or pledged for not repeating the offense. In some cases, TPS may impose more severe penalties. The offender had to prepare breakfast, lunch, or dinner for more than ten people, which was considered one of the harshest penalties due to the low standard of living at the time. Most of the villagers worked cooperatively to protect their property, including forests, farmlands, and pastures. Thus, the inhabitants of the rural community with their limited knowledge at that time were trying to safeguard as much as possible the forests and pastures surrounding them.

About five decades ago, all the forests and forestlands in the south-western region of KSA had been converted to state lands. With the passage of time and changing socio-economic conditions of the country, accompanied with migration from the countryside to big cities, the natural forests in the southwest were exposed to overgrazing and fires, and no care had been taken in terms of silviculture and protection. Therefore, the government issued regulations to protect the natural forestland, including the 1978 Forestry and Rangeland Regulation. This regulation dealt with the protection of forests and rangelands and the regulation of their use. It regulates fuelwood collection, transportation, and charcoal production activities through licenses. But this vital region, representing a unique ecosystem within the country, still needs a lot of efforts with different administrative arrangements in order to hold on to its original landscape and sustainable forests management.

In terms of achievements in the area of sustainable forest management, the KSA's national strategy focuses on environmental sustainability. Forest and biodiversity resources are not explicitly included in the stated goals, but the focus on environmental and natural resource protection is clear. The ninth strategic goal focuses on preserving vegetation and forests. The proportion of the country's total forest area that is revegetated each year is the most important indicator for gauging success. Only 0.06% of the total forest area has been regenerated so far, but by the end of 2020, that number was predicted to rise to 60,000 ha of land, which is 0.11% (Alshuwaikhat and Mohammed 2017).

10.2 Case Studies from Pakistan

The 'Billion Tree Tsunami,' Khyber Pakhtunkhwa

As a result of decades of logging and natural disasters, Pakistan's forests have been severely depleted and forest cover of the country is estimated to be 2% out of 5% forest land. Pakistan's forest cover is well below the UN's suggested level of 12%, and it is one of the least forested countries of the area. In addition, it is one of the six countries that will feel the more consequences of climate change. Due to deforestation, flooding and landslides were more likely to occur in Khyber Pakhtunkhwa. The province was devastated by flash floods in 2016 that killed hundreds of people.

To reverse such trends, in 2021, Pakistan achieved its billion tree objective. Khyber Pakhtunkhwa, a province in northwest of the country, is now quite vibrant with newly planted seedlings. The 'Billion Tree Tsunami,' a mega project, added 350,000 hectares both by planting and spontaneous regeneration in attempt to re-establish the province's degraded forests and combat the impact of climate change.

The government in the province of Khyber Pakhtunkhwa in Pakistan launched the Billion Tree plantation project in 2014 with the implementation costs of US $680 million. For more than just environmental benefits, this project has helped raise local wages and created green jobs, particularly for jobless men and women in the region. The government of Khyber Pakhtunkhwa exceeded its Bonn Challenge target of 348,400 ha. Deforested land around the world is expected to be restored by 2020, and 350 million hectares by 2030, as a result of the above. The International Union for Conservation of Nature's (IUCN) Chief Inger Andersen, in charge of administering the Bonn Challenge, called it a 'genuine conservation success story' (World Economic Forum 2018).

Soon Valley Development Program, Noorpur Thal

The Soon Valley Development Program (SVDP) was planned to develop an innovative farming system-based livelihood model for Noorpur Thal, Punjab, Pakistan. Noorpur Thal, a tehsil of district Khushab, is part of Thal Daob, having an area of about 2500 km^2 with an estimated population of 239,051 individuals over its ten union councils and 82 villages.

A probing study was initiated by SVDP, in collaboration with other development partners, for the identification of real challenges and their possible solutions in the area of sustainable agricultural development in Thal. The study was funded by the Pakistan Poverty Alleviation Fund (PPAF) and conducted by the Social Sciences Research Institute through the PARC Agro-Tech Company (PATCO) by engaging a multidisciplinary team of experts from water, range, and livestock professions. We believe that the findings of this study will be utilized as a guide for developing efforts to enhance livelihoods in other vulnerable areas of country. SVDP has a rich experience of 17 years in sustainable development, poverty alleviation, and livelihood improvement through the promotion of alternative energy sources and a high efficiency irrigation system. SVDP has also implemented several other development initiatives in livestock sector, off-season vegetable cultivation, cooperative marketing, and organic production. The following are the main outcomes of this study:

- The study, which is based on deliberate, participatory process, started in March 2013. An objective-based assessment was made through multiple visits and stakeholder consultations, including community and line departments, followed by a rigorous review of literature related to past practices and knowledge relevant to the area.
- The study provided an evaluation of concerns and possibilities as well as the technical feasibility of possible interventions for poverty reduction and economic growth through the sustainable use of natural resources in Noorpur Thal.
- The livelihoods in Noorpur Thal are shaped by a multitude of different forces and factors among which natural resources are driving factors. Hence, all livelihood

improvement and diversification strategies have to be based on the sustainable use of natural resource in the concerned area.

An innovative approach for rural development has been established in six union councils in the Soon Sakesar, Khushab Valley, which focuses on the need to develop natural resources. The area has seen an increase in its annual income while at the same time preserving its most precious natural resources, such as groundwater.

The aim of SVDP was to launch different programs in areas like groundwater sustainable harvesting, crop production, forestry, dairy, and livestock sectors. However, before initiating the program at a large scale, SVDP had planned to conduct a feasibility study by involving sectoral experts. The objective of the study was to develop alternate technical options with feasibility analyses while considering the availability of groundwater resources used for crops, livestock, and forestry inventions. Furthermore, the technical possibilities were designed to benefit the people by boosting their economic well-being and alleviating poverty by ensuring the sustainable use of resources and protecting the environment. Using this information, it was possible to create a development plan for Noorpur Thal that could be used in other Thal regions as well. The main purpose of this was to transform the Thal desert into fertile agricultural land, which would increase food production and improve living standards (Shah et al. 2013).

11 Conclusions and Recommendations

In KSA, the predicted impacts of the climate change include rising temperatures and increased carbon dioxide levels. The rise of Earth's temperature and the increase of carbon dioxide levels in the atmosphere are currently measured facts, and related figures are being recorded over the past decades. Therefore, climate change may have severe impacts on ecosystems. Many studies have indicated that KSA is also experiencing such impacts, especially on forest ecosystems' health and associated services. It is anticipated that climate change would not only decrease wood volumes in stressed environments, but also have negative impacts on other tangible and intangible benefits. Therefore, it is important to conduct scientific studies to gauge such impacts on forest's health and associated services and goods.

Deforestation is key source of carbon emissions, and by simply halting forest removal and stopping tree harvesting, we can help mitigate climate change. The role of local communities seems very pivotal in managing forests and ensuring their protection and sustainability on a long-term basis. The above analysis suggests vibrant forestry extension programs, aiming to enhance the participation of locals and other stakeholders. Moreover, technical and scientific studies to evolve the workable solutions, awareness-creating campaigns, and forestry extension education programs would remain equally important.

References

Abdulkareem A, Ellaboudy A (2019) Spotlight activity: Saudi Arabia signals increased acceptance of climate change risks and willingness to invest in renewable energy. Saudi Arabia News Brief and Action Alert. Climate Scorecard

Abo-Hassan AA, El-Osta MLM, Sabry MM (1984) Natural forests in the Kingdom of Saudi Arabia and the possibility of exploiting them economically. National Center for Science and Technology (Now: King Abdulaziz City for Science and Technology), Book, (1)

Agbogidi OM, Ofuoku AU (2009) Forestry extension: implications for forest protection. Int J Biodivers Conserv 1(5):098–104

Ahmad BI, Khan RA, Siddiqui MT (2013) Incidence of dieback disease following fungal inoculations of sexually and asexually propagated Shisham (*Dalbergia sissoo*). Forest Pathol 43(1):77–82

Ahmad I, Atiq M, Gul S, Hannan A, Siddiqui MT, Nawaz MF, Ahmed S (2016) Dieback disease predictive model for sexually and asexually propagated *Dalbergia sissoo* (Shisham). Pak J Bot 48(4):1645–1650

Alahmed AM, Kheir SM, Al-Khereiji MA (2010) Distribution of Culicoides latreille (Diptera: Ceratopogonidae) in Saudi Arabia. J Entomol 7(4):227–234

Al-Eisawi D (2012) Conservation of natural ecosystems in Jordan. Pak J Bot 44(Suppl. 2):95–99

Al-Hemaid FMA (2007) The dieback of the juniper forests in Saudi Arabia, a field trip report. Department of Botany and Microbiology, College of Science, King Saud University

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier MM, Kitzberger T, Rigling A, Breshears DD, Hogg ET, Gonzalez P (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manage 259(4):660–684

Al Nafie AH (2008) Phytogeography of Saudi Arabia. Saudi J Biol Sci 15(1):159–176

Alshuwaikhat HM, Mohammed I (2017) Sustainability matters in national development visions—evidence from Saudi Arabia's vision for 2030. Sustainability 9(3):408

Al-Subaiee FS (2014) Attitudes of locals and their dependence on the natural forests: a case study of Al-Baha area-Saudi Arabia. J Anim Plant Sci 24(2):634–650

Aref IM, El-Juhany LI (2000) Natural and planted forests in Saudi Arabia; their past present and future. Arab Gulf J Sci Res 18(1):64–72

Assaeed MA, Al-Doss AA (2002) Soil seed bank of desert range site infested with Rhazya stricta in Raudhat al-khafs, Saudi Arabia. Arid Land Res Manage 16:83–95

Auclair AN, Heilman WE, Brinkman B (2010) Predicting forest dieback in Maine, USA: a simple model based on soil frost and drought. Can J for Res 40(4):687–702

Badai KH, Aldawoud AN (2004) The natural forests in Saudi Arabia

Baig MB, Pulhin J, El-Juhany L, Straquadine GS (2019) Ensuring sustainability in forests through the participation of locals: implications for extension education. In: Behnassi M, Pollmann O, Himangana G (eds) Climate change, food security and natural resource management: perspectives from Africa, Asia and the Pacific Islands. Springer International Publishing, Switzerland, pp 323–360. https://doi.org/10.1007/978-3-319-92828-9

Chaudhary SA (1997) Flora of the Kingdom of Saudi Arabia, vol 1. National Agriculture and Water Research Centre. Ministry of Agriculture, Saudi Arabia, p 691

Chaudhary SA, Le Houérou HN (2006) The rangelands of the Arabian Peninsula. Sci Et Changements Planétaires/Sécheresse 17(1):179–194

Doha SA (2009) Phlebotomine sand flies (Diptera: Psychodidae) in different localities of Al-Baha province, Saudi Arabia. Egypt Acad J Biol Sci, E Med Entomol Parasitol 1(1):31–37

El-Juhany LI (2009) Forestland degradation and potential rehabilitation in southwest Saudi Arabia. Aust J Basic Appl Sci 3(3):2677–2696

El-Juhany LI (2014) Cross section characteristics and age estimation of Juniperus procera trees in the natural forests of Saudi Arabia. J Pure Appl Microbiol 8(Spl. Edn. 2):657–665

El-Juhany L (2015) The magnitude of dieback on Juniperusprocera trees in the natural forests in the southwestern region of Saudi Arabia. Biosci Biotechnol Res Asia 12(1):219–230
El-Juhany LI, Aref IM (2012a) The present status of the natural forests in the Southwestern Saudi Arabia 2-baha forests. World Appl Sci J 20(2):271–281
El-Juhany LI, Aref IM (2012b) The present status of the natural forests in the southwestern Saudi Arabia: 1-Taif forests. World Appl Sci J 19(10):1462–1474
El-Juhany LI, Aref IM (2013) The present status of the natural forests in the southwestern Saudi Arabia: 3-Asir and east Jazan forests. World Appl Sci J 21(5):710–726
El-Juhany LI, Aref IM, Al-Ghamdi MA (2008) The possibility of ameliorating the regeneration of juniper trees in the natural forests of Saudi Arabia. Res J Agric Biol Sci 4(2):126–133
El-Osta MLM (1983) Estimation of volume of standing timber in the south-western region of Saudi Arabia. J Coll Agric, King Saud Univ
FAO (2007) State of the world forests 2007. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy
FAO (2009) Global review of forest pests and diseases, PART I: regional and global analysis, Near East, p 32. FAO Forestry Paper 156. Food and Agricultural Organization, Rome, Italy
FAO (2010) Global Forest Resources Assessment 2010 (FRA 2010) main report, p 226
FAO (2011) State of the world's forests 2011. Food and Agriculture Organization of the United Nations (FAO), Rome
FAO (2016) State of the world's forests 2016: forests and agriculture: land-use challenges and opportunities. FAO Report
FAO/RNE (2011) Regional priority framework for the Near East. FAO Regional Office for the Near East, Cairo
Fisher M (1997) Decline in the juniper woodlands of Raydah Reserve in southwestern Saudi Arabia: a response to climate changes? Glob Ecol Biogeogr Lett 379–386
Galal TM, Al-Yasi HM, Fadl MA (2021) Vegetation zonation along the desert-wetland ecosystem of Taif Highland, Saudi Arabia. Saudi J Biol Sci 28(6):3374–3383
Gardner AS, Fisher M (1994) How the forest lost its trees: just so storytelling about Juniperus excelsa in Arabia. J Arid Environ 26(3):299–301
Hérault B, Piponiot C (2018) Key drivers of ecosystem recovery after disturbance in a neotropical forest. For Ecosyst 5:2. https://doi.org/10.1186/s40663-017-0126-7
Honke JS, Pigati JS, Wilson J, Bright J, Goldstein HL, Skipp GL, Reheis MC, Havens JC (2019) Late quaternary paleohydrology of desert wetlands and pluvial lakes in the Soda Lake basin, central Mojave Desert, California (USA). Quatern Sci Rev 216:89–106
Jewitt S (1996) Agro-ecological knowledges and forest management in the Jharkhand, India: Tribal development or populist impasse? Doctoral dissertation, University of Cambridge
Joint Liaison Group of the Rio Conventions (2008) Forests: climate change, biodiversity and land degradation. http://www.cbd.int/doc/publications/for-cc-2008-en.pdf
Kaewkrom P, Kaewkla N, Thummikkapong S, Punsang S (2011) Evaluation of carbon storage in soil and plant biomass of primary and secondary mixed deciduous forests in the lower northern part of Thailand. Afr J Environ Sci Technol 5(1):8–14
Macura B, Zorondo-Rodríguez F, Grau-Satorras M, Demps K, Laval M, Garcia CA, Reyes-García V (2011) Local community attitudes toward forests outside protected areas in India. Impact of legal awareness, trust, and participation. Ecol Soc 16(3)
Marland G, Pielke RA Sr, Apps M, Avissar R, Betts RA, Davis KJ, Frumhoff PC, Jackson ST, Joyce LA, Kauppi P, Katzenberger J (2003) The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. Climate Policy 3(2):149–157
Miller AG (1994) Highlands of south-western Arabia: Saudi Arabia and Yemen. Centres Plant Divers 1:317–319
Ministry of Agriculture (2002) Forestry strategy and work plan in Saudi Arabia. Ministry of Agriculture, Riyadh, Saudi Arabia

Ministry of Economy and Planning (2005) The eighth development plan. Ministry of Economy and Planning, Riyadh, Saudi Arabia

NCWCD (2005) The national strategy for conservation of biodiversity in the Kingdom of Saudi Arabia. Prepared and Issued by the National Commission for Wildlife Conservation and Development (NCWCD), Saudi Arabia

NCWCD & JICA (2006) The management plan for conservation of Juniper woodlands. The final report of the joint study conducted by the National Commission for Wildlife, Conservation and Development (NCWCD) and Japan International Co-operation Agency (JICA)

Ozturk A, Saglam B, Barli Ö (2010) Attitudes and perceptions of rural people towards forest protection within the scope of participatory forest management: a case study from Artvin, Turkey. Afr J Agric Res 5(12):1399–1411

Regent Honeyeater (2014) Understanding dieback. Available at: http://regenthoneyeater.org.au/dieback.php

Ross C (2013) Fact sheet: dieback in south-east Australia. Greening Australia. www.murrumbidgeelandcare.asn.au/files/Dieback%20fact%20sheet.pdf

Saikku L, Soimakallio S, Pingoud K (2012) Attributing land-use change carbon emissions to exported biomass. Environ Impact Assess Rev 37:47–54

Sanquetta CR, Dalla Corte AP, Maas GB (2011) The role of forests in climate change. Quebracho-Rev Cienc Forestales 19(1–2):84–96

Saudi Geological Survey (2012) Facts and numbers (In Arabic)

Schulz E, Whitney JW (1986) Vegetation in north-central Saudi Arabia. J Arid Environ 10(3):175–186

Shah H, Khan MA, Ashraf A, Cheema AU, Aslam M, Ahmad S (2013) Poverty alleviation and economic growth through sustainable use of natural resources in Noorpur Thal. A technical study conducted through PATCO for SVDP. Social Sciences Research Institute, National Agricultural Research Centre, Islamabad, Pakistan

Sirivongs K, Tsuchiya T (2012) Relationship between local residents' perceptions, attitudes and participation towards national protected areas: a case study of Phou Khao Khouay National Protected Area, central Lao PDR. Forest Policy Econ 21:92–100

Steinkamp J, Hickler T (2015) Is drought-induced forest dieback globally increasing? J Ecol 103(1):31–43. http://www.jstor.org/stable/24542182

Tesfaye Y, Anders R, Folke B (2012) Attitudes of local people towards collective action for forest management: the case of PFM in Dodola area in the Bale Mountains, Southern Ethiopia. Int J Biodivers Conserv 21:245–265

Tolba MK, Saab N (2009) Arab environment: climate change: impact of climate change on Arab countries. Arab Forum Environ Dev (AFED)

Triguero-Mas M, Olomí-Solà M, Jha N, Zorondo-Rodríguez F, Reyes-García V (2009) Urban and rural perceptions of protected areas: a case study in Dandeli Wildlife Sanctuary, Western Ghats India. Environ Conserv 36(3):208–217

UN Statistics Division (2012) Country profiles—Saudi Arabia. Available at: http://data.un.org/Country Profile.aspx? Crname Saudi Arabia. Accessed on 28 Jan 2012

WeatherOnline (2020) https://www.weatheronline.co.uk/reports/climate/Saudi-Arabia.htm

World Economic Forum (2018) https://www.weforum.org/agenda/2018/07/pakistan-s-billion-tree-tsunami-is-astonishing/. Accessed on: 10 Sept 2021

Dr. Irfan Ahmad is an Associate Professor and in charge of the experimental area in the Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan where he is serving as a Faculty Member since 2007. His research interests lie in the areas of agroforestry, forest protection and management, forest ecology, phytoremediation, and forest nursery establishment.

Dr. Muhammad Farrakh Nawaz is currently working as an Associate Professor at the Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan. He has investigated the environmental services of trees, climate change mitigation through carbon sequestration by integrated land use, phytoremedial potential of trees for reclaiming degraded soils, and the impact of mechanized operations in forests.

Dr. Muhammad Asif is currently working as a Lecturer at the Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan. He has a research experience in forest management, silviculture, and mensuration.

Dr. Muhammad Haroon U Rashid is currently working at the Department of Forestry and Range Management, University of Agriculture Faisalabad, Pakistan. He is a 'Forest Ecologist' having research experience in silviculture, forest cultivation, stand productivity, including nutrient cycling and environmental conservation in forest ecosystems.

Dr. Mehak Shaheen is currently working as a Lecturer at the Department of Forestry, Range and Wildlife, Ghazi University, Dera Ghazi Khan, Pakistan. She has expertise in forest ecology, phytoremediation, and medicinal Plants.

Human–Wildlife Conflict: The Case of Crop Raiding and Its Socio-economic Implications Around Pendjari Biosphere Reserve, Northern Benin

Sylvain Efio, Etotépé A. Sogbohossou, Yves Z. Magnon, Bertrand Hamaide, Marcel R. B. Houinato, François M. Habiyaremye, Rigobert C. Tossou, and Brice A. Sinsin

Abstract Human–wildlife conflict is becoming a serious threat for both wildlife conservation and human well-being. Its main representations are livestock predation and crop raiding. This chapter examines the problem of crop raiding by wildlife and its socio-economic implications around Pendjari Biosphere Reserve in northern Benin. Data were collected in 2017 through field observations, semi-structured interviews, and a questionnaire survey of 209 farmers of the surrounding villages of the reserve, and 98% of them reported losses of crop every year due to wildlife. Crops with the highest degree of destruction are cotton, maize, millet, and sorghum, and the wild animals responsible for this are mainly baboon, warthog, and elephant. Crop raiding causes, for an average farmer, an annual financial loss ranging from $94.64 in farms of sorghum to $311.8 in farms of cotton. Compared to the annual minimum salary in Benin, these numbers are considerable. Farmers try to manage the impacts of crop raiding with various mitigation measures such as guarding, but the heavy toll of crop raiding and the low level of effectiveness of such measures clearly reveal the vulnerability of agricultural households bordering protected areas.

Keywords Crop raiding · Benin · Economic losses · Pendjari biosphere reserve · Survey

S. Efio (✉) · B. Hamaide
Center for Research in Economics, Université Saint-Louis, Brussels, Belgium
e-mail: sylvain.efio@usaintlouis.be

B. Hamaide
e-mail: bertrand.hamaide@usaintlouis.be

S. Efio · Y. Z. Magnon · R. C. Tossou
Laboratory of Sociology and Rural Extension, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

E. A. Sogbohossou · M. R. B. Houinato · B. A. Sinsin
Laboratory of Applied Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

F. M. Habiyaremye
Royal Belgian Institute of Natural Sciences (RBINS), Brussels, Belgium
e-mail: fmuhashy@naturalsciences.be

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_16

1 Introduction

Social–ecological systems are composed of interdependent and interacting ecosystems and human communities (Berkes et al. 1998; Folke et al. 2010). Humans' interactions with the ecological environment can be positive or negative (Redpath et al. 2015; Fisher 2016). Positive interactions or ecosystem services refer to the benefits that human societies derive from nature. These benefits are divided by the Millennium Ecosystem Assessment (2005) into four groups: regulatory services, support services, supply services, and cultural services. Supply services are goods produced or obtained from ecosystems such as food, water, wood, fibers, and materials. As for cultural services, they include recreational (i.e., hiking and ecotourism) and cultural pleasures, aesthetic values, as well as the educational interest offered by nature, or even spiritual enrichment. Air and water purification are classified in regulatory services, and support services are services that underpin all of the above services, for example nutrient cycling. The negative interactions of humans with their environment take into account, among other things, the problematic relations of locals with wildlife. These negative human–wildlife interactions have been a reality faced by mankind since the beginning of its existence (Lamarque et al. 2009). Human–wildlife conflicts are any interactions with a negative impact for both parties. Human–wildlife conflict has traditionally been viewed to occur "when the needs and behavior of wildlife impact negatively on the goals of humans or when the goals of humans negatively impact the needs of wildlife" (Madden 2004).

Conflicts are more frequent in the peripheries of protected areas and include, among others, attacks by humans (Packer et al. 2005), the depredation of crops and granaries (Pimentel et al. 2005; Perez and Pacheco 2006), the predation of cattle, transmission of disease to livestock and humans, and the opportunity costs where local residents abandon certain economic or life choices because of the presence of wild animals or protected areas (Thirgood et al. 2005). But the most important forms of manifestation of human–wildlife conflicts in the world are crop depredation and livestock predation (Mhuriro-Mashapa et al. 2018), with crop depredation being the most pressing issue in Africa (Lamarque et al. 2009; Fairet 2012).

Many authors are increasingly interested in crop raiding in Africa: Biset et al. (2019) in Ethiopia; Nsonsi (2018) in Gabon; Kouao et al. (2018) in Ivory Coast; and Fairet (2012) in Gabon. The latter studied crop raiding around Longo National Park and assessed the vulnerability of households there. In Benin, Sogbohossou et al. (2017) and Dossou et al. (2019) studied the crop raiding around the Mono Delta Transboundary Biosphere Reserve in Southwest Benin and Ouémé River area in central Benin, respectively.

Within the same perspective, this chapter examines the extent and patterns of crop raiding and the financial impacts and determinants of crop raiding by wildlife in the Pendjari Biosphere Reserve, northern Benin. The remainder of the text is organized as follows: Sect. 2 details the study zone and data collection; the results of the analysis are presented in Sect. 3; and the discussion is presented in Sect. 4 followed by concluding remarks.

2 Methodology

2.1 Study Area

The study was carried out around Pendjari Biosphere Reserve in Atacora department, north-west Benin (Fig. 1). It represents one of the better managed protected areas in West Africa semi-arid regions. The south of the reserve is bordered by the Atacora Mountain chain (elevation of 400–500 m altitude), which is directly connected to the mountain of northern Togo. Apart from these mountains and a few isolated hills, the topography of the reserve is flat, ranging between 150–200 m above sea level (Delvingt et al. 1989). The reserve is part of a complex of four adjoining protected areas W, Arly, Pendjari, and Oti-Mandouri (WAPO) in four adjacent countries (Benin, Burkina Faso, Niger, and Togo). The Pendjari Biosphere Reserve was established in 1954, upgraded to National Park status in 1961, and to a UNESCO Man and Biosphere Reserve in 1986. It comprises Pendjari National Park (2.660 km^2), Pendjari and Konkombri Hunting Zones (1.600 km^2 and 251 km^2, respectively), and a buffer zone with controlled land-use access for local people (340 km^2). The Reserve is bordered to the north and west by the Pendjari River and to the east by the Atacora Mountain range (CENAGREF 2016).

In this Sudanian ecosystem, the climate is characterized by a dry season from October to May and a wet season with a total annual rainfall of 800–1000 mm. The vegetation is a mixture of open grass and tree savannahs interspersed with dry and

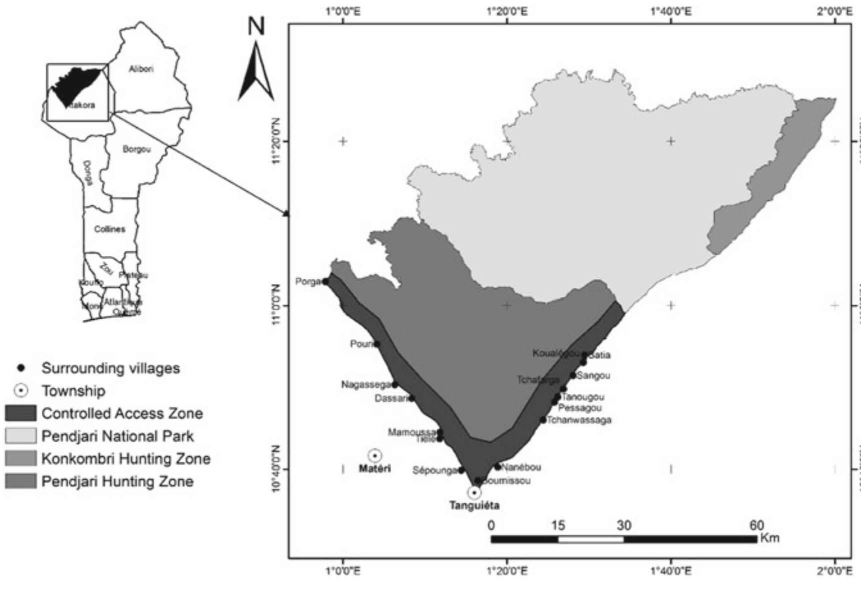


Fig. 1 Pendjari Biosphere Reserve and the surrounding villages

gallery forests. The fauna of the Pendjari Biosphere Reserve is typical for this region of West Africa (Kouton et al. 2019). There are eleven different species of antelopes; some emblematic species—such as the cheetah, the elephant, the lion, and the African wild dog—are in Pendjari Biosphere Reserve. The leopard is also present. In addition, Ahouansou Montcho et al. (2009) have identified 378 bird species and 62 fish species from 21 families, Nago et al. (2006) 17 amphibian species, and Djossa et al. (2008) 28 species of flying foxes.

Agriculture and breeding are the main activities of the local communities in the villages surrounding the Reserve (Houinato and Sinsin 2000). But agriculture is subject to a number of constraints, including the insufficiency of cultivable land, in particular on the Tanguiéta-Batia axis, where populations are trapped between the Atacora chain and the Reserve, which reduces the duration of the fallow; soil poverty; erosion; irregular and insufficient rain; and the depredation of crops by fauna (Lokossou et al. 2018).

2.2 Data Collection and Analysis

Data on crop raiding and management measures were collected through field observations, semi-structured interviews, and questionnaire survey between January and February 2017. The questionnaires are not placed in Appendix because of lack of space, but they are of course available upon request. Three main criteria prevailed in the choice of villages to be surveyed: the proximity of the village to the Pendjari Biosphere Reserve; the socio-cultural group; and the extent of animal damage. On the basis of these criteria, 15 villages were chosen in the municipalities of Tanguiéta and Materi (Fig. 1). The managers of the protected area and the farmers from the local communities were questioned. Questions were related to crop raiding manifestations, mitigation measures, and socio-economics implications. A total of 209 farmers participated in the study. One person per household was interviewed. Data were analyzed using SPSS v.16. Descriptive statistics were used to depict crop raiding. We used for each crop mean yield the prices obtained from the Beninese Office of Food Security (Office National de Sécurité Alimentaire, ONASA) in December 2016 to evaluate the economic impact of human–wildlife conflicts. Those prices were converted from XOF to US dollar using the USD value of September 1, 2017 (1 USD = 550 XOF).[1] More precisely, data collection and computations enabled us to determine costs per farmer. For proceeding as such, we first determined the average area cultivated by a farmer for each of the four main crops (cotton, maize, sorghum, and millet).

[1] www.mataf.net/fr/conversion/monnaie-USD-XOF.

Table 1 Socio-demographic characteristics of respondents

Variables	Characteristics			
Ethnicities (%)	Berba (50.7)	Gourmantché (26)	Wama (17.7)	Boulba (4.3)
Marital status (%)	Single (3.3)	Married (93.3)	Widow (3.3)	–
Instruction (%)	Uneducated (55.5)	Elementary school (29.2)	High school (15.3)	–
Sex	Male (94.3%, $n = 197$)		Female (5.7%, $n = 12$)	
Age (years)	Min (19)	Max (70)	Mean (41.15)	SD (10.38)

3 Results

3.1 *Respondents' Demographic and Socio-economic Characteristics*

All respondents were farmers from the three main ethnic group surrounding the Reserve: Berba (50.7%), Gourmantché (26%), and Waama (17.7%). The age group of the respondents ranged from 19 to 70 years old, with an overall mean age of 41.15 ± 10.38 (SD) years. Overall, more males (94.3%, $n = 197$) than females (5.7%, $n = 12$) participated in this survey, probably because the Beninese rural women do not speak in the presence of men or because women deferred to men in seniority. Those interviewed here were either widows or because of the absence of their husbands (Table 1).

3.2 *Farming Activities Around Pendjari Biosphere Reserve*

Agriculture is the main activity and source of income for local communities around the Pendjari Biosphere Reserve. All respondents were farmers with 18.64 (SD = 9.7; $n = 163$) years of experience in farming activities. Farms were at an average distance of 2.9 km (SD = 1.7 and $n = 208$) from the villages. The mean farm size per household was 5.03 ha (SE = 0.22; $n = 205$), and there was an average of 5.12 agricultural workers by household (SD = 2.5; $n = 170$). The main crops produced were cotton 2.56 ha (SD = ± 1.5; $n = 100$), maize 2.02 ha (SD = ± 1.16; $n = 205$), sorghum 1.27 ha (SD ± 0.67; $n = 89$), and millet 1.5 ha (SD = ± 0.98; $n = 46$). Farming activities are displayed in Table 2.

Table 2 Farming activities characteristics

Variables	Number (*n*)	Mini	Maxi	Mean	SD
Experience in agriculture (years)	163	3	50	18.64	9.7
Agricultural workers/household	170	1	14	5.12	2.5
Cultivated area (ha)	205	0.5	21	5.03	3.1
Distance of farm from home (km)	208	0.2	10	2.9	1.7

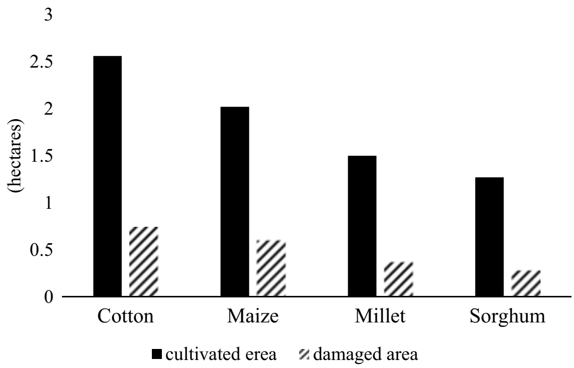


Fig. 2 Main crops damaged by wildlife around Pendjari Biosphere Reserve. *Source* Developed by the authors

3.3 Crop Raiding

Crop raiding is a real problem facing farmers in the peripheries of the Pendjari Biosphere Reserve. Figure 2 shows damages to the main crops considered.

In absolute value (hectares damaged), cotton is much more problematic than sorghum; but it is not the case since all considered crops are very much hit given that the percentages of damaged cultures range from 22 to 30%.

3.4 Crop Raiders

Several wildlife species are involved in crop raiding. Around the Pendjari Biosphere Reserve, Baboon, warthog, and elephant are the main crop raiders (Fig. 3). While damages by warthogs and elephants are recorded at the time of crop maturity and harvest time, damages of baboons are recorded all along the agricultural season, which may explain the high percentage of their citation by local populations.

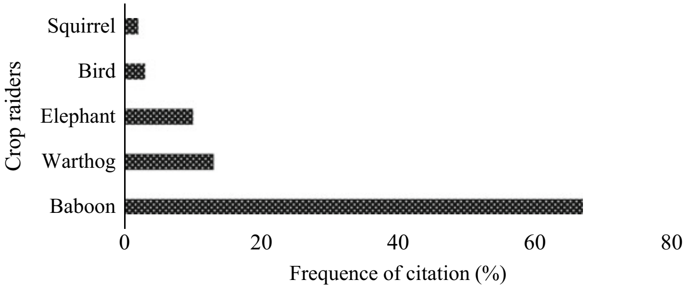


Fig. 3 Main crop raiders around Pendjari Biosphere Reserve. *Source* Developed by the authors

3.5 Economic Impact of Crop Raiding

The economic impact of human–wildlife conflicts was evaluated considering annual crops destroyed per farmer. Farmers can lose from \$94,64 in sorghum farm to \$311,8 in cotton farm (Table 3).

Considering the average yield per crop and the production loss (Fig. 2) due to animal interactions (Fig. 3), and considering the average crop price, we were able to determine, in local currency, the annual loss per crop type. Converting these numbers in USD revealed that an average farmer loses around \$312 for cotton production, \$255 for maize, \$104 for millet, and \$95 for sorghum. These numbers are not trivial. As a matter of fact, for illustration purposes, suppose that the average farm size is 5.03 ha as mentioned above in Sect. 3.2 and that such a standard farm includes production of all four crop types in proportion of its average area mentioned in Table 3 (i.e., 1.75 ha, 1.38 ha, 1.03 ha, and 0.87 ha for cotton, maize, millet, and sorghum, respectively). Computing lost quantity, annual loss in XOF converted in USD gives us a loss of \$213 for cotton, \$174 for maize, \$71 for millet, and \$65 for sorghum. The overall

Table 3 Economic cost of crop raiding

Crops	Cotton	Maize	Millet	Sorghum
Average cultivated area (ha)	2.56	2.02	1.5	1.27
Average yield (kg/ha)	1100	1680	940	1150
Average production (kg)	2816	3393.6	1410	1460.5
Proportion of loss (%)	29	30	25	22
Quantity lost (kg)	816.64	1018.08	352.5	321.31
Average price/kg (XOF)	210	138	162	162
Agricultural income (XOF)	591,360	468,317	228,420	236,601
Annual loss (XOF)	171,494.4	140,495	57,105	52,052
Annual loss (US\$)	311.8	255.45	103.82	94.64

Note \$1 = 550 FCFA
Source Developed by the authors

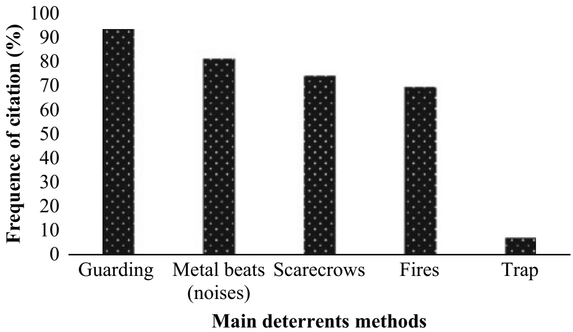


Fig. 4 Farmers' crop raiding coping strategies around Pendjari Biosphere. *Source* Developed by the authors

annual loss of that average hypothetical farmer is therefore $523. When compared with the minimum wage of some $873 a year (40,000 XOF a month since 2018), it is easy to see that human–wildlife conflict may indeed have very important economic consequences.

3.6 Mitigation Measures

Farmers develop some strategies to cope with crop raiding. These strategies are mainly guarding, noises, and scarecrows (Fig. 4).

Guarding is the most used (93%) coping strategy by farmers surrounding the Pendjari Biosphere Reserve. Farmers generally seat on strategic watchtowers (tall trees) to guard their farms against raiders. Children also go around the field by shouting. Making noise with metallic objects (81%) is often associated to guarding. At sunset, some farmers make fires with green branches (69%) to deter animals with the smoke. Others spend the night in fields under huts with flashlights to deter nocturnal raiders like elephants and warthogs and animals frequently appearing around sunrise like baboons. Guarding is time-consuming for farmers, especially when the farm is relatively large. They often (74%) use scarecrows made from salvage items. Traps, which are banned, are rarely used as they harm the survival of wildlife species.

4 Discussion

We focused our study on crop raiding, the most important form of human–wildlife conflict in Africa (Lamarque et al. 2009) and around the Pendjari Biosphere Reserve (Efio et al. 2018). It was observed that cotton, maize, millet, and sorghum were the main crops destroyed by wild animals, the most important of which were baboon, warthog, and elephant. These crops were also those identified by Sogbohossou et al. (2017) and Dossou et al. (2019) as the main crops destroyed by hippopotamus in the Mono Delta Transboundary Biosphere Reserve in Southwest Benin and along the Ouémé River in central Benin, respectively. Like in Cameroon (Weladji and Tchamba 2003), baboon, warthog, and elephant were the most important crop depredators. Elephant, which is usually the most important threat to crops (Parker et al. 2007), was not the first raider around Pendjari. This can be explained by the fact that villages are separated from the protected area by a buffer zone and the density of most wildlife is very low close to villages. One exception is baboon, which can also be found on the mountain bordering villages in the eastern part of the Reserve and hills found in the western side villages. This is because the baboons are not afraid of humans and they are present in villages. Half of the villages is bordered by the Atacora Mountain, which is home to baboons too.

Whether in the North of Benin around the Pendjari Biosphere Reserve, in the Southwest around the Mono Delta Transboundary Biosphere Reserve or in central Benin along the Ouémé River, the main crops destroyed were cereals and cotton. If damages during sowing could be repaired by another sowing, damages during the harvest period are unrecoverable. This indicates that the crop raiding threatens households' food (Barua et al. 2013) and economic security, since cotton is the main cash crop of Beninese farmers and Benin is the leading producer of cotton in Africa (WTO 2020). Human–wildlife conflicts caused an average loss of 25% of the cultivated area around the Pendjari Biosphere Reserve, which results in an annual loss ranging from \$94.64 to \$311.8, depending on the type of crop. This value is similar to the cost of damage to hippopotamus around the Mono Delta Transboundary Biosphere Reserve estimated at \$254.54 by Sogbohossou et al. (2017). This cost could seem insignificant, but it constitutes a heavy tribute for these poor local communities which live on less than a dollar a day. To limit the impact of wildlife's damage on their livelihoods, local communities develop measures that very often boil down to deterrence mechanisms and are rarely effective (Nyhus 2016; Efio et al. 2018).

Mitigation measures used by populations around the Pendjari Biosphere Reserve were non-lethal. This is quite positive as local communities did not seem to think about retaliatory killing as a way to reduce predation, which is contrary to other parts of Africa where wildlife pays a heavy tribute due to conflicts (Nowell and Jackson 1996; Balme 2009). As already highlighted by Sogbohossou (2011) and Sogbohossou et al. (2011), local communities around Pendjari have a rather positive attitude toward the protected area that they considered as their heritage and a source of revenue through tourism.

The oldest and most widely used deterrence method in the Pendjari Biosphere Reserve is guarding, and it seems to be the most effective human–wildlife conflicts management measure (Nyhus 2016). However, the costs of labor and the need for constant vigilance are the key drawbacks of this approach (Tehou et al. 2018). This method can be effective both against crop raiders and livestock depredators; however, its efficiency is limited against nocturnal depredators as it is difficult to guard farms during the night. Fire, used to dissuade nocturnal predators, is also not a prominent measure because fire made with dry wood does not last long enough to prevent animals to visit cultivated areas (Conover 2002; Linnell et al. 2012).

The heavy toll of human–wildlife conflicts and the low level of effectiveness of measures to manage the crop raiding clearly reveal the vulnerability of agricultural households bordering protected areas. This concept of vulnerability has been introduced into the literature on human–wildlife conflicts since the 1990s by Naughton-Treves (1997). The author defined it as the degree to which farm households are exposed to the risk of damage from wild animals, combined with their individual abilities to deal with damage. Two years later, Naughton et al. (1999) refined this definition by including the individual and collective dimensions of man–wildlife conflict management measures.

Focusing on the vulnerability of agricultural households to crop raiding around Longo National Park in Gabon, Fairet (2012) identified three dimensions of vulnerability: institutional, biophysical, and social. The same three dimensions of households' vulnerability to crop raiding can be found in the Pendjari Biosphere Reserve. The institutional vulnerability comes from the classical top-down conservation strategies, excluding local populations from the decision-making process (Adams 2004; Adams and Hutton 2007). These conservation regulations may indeed hinder farmers' ability to protect themselves against raiding animals (Thirgood et al. 2005), thereby creating a form of institutional vulnerability (Fairet 2012). The biophysical vulnerability results from the proximity of wild animals, and, in our case study, it is greatly aggravated by the geomorphological conditions of the region (Kiansi 2011). Finally, the social vulnerability is due to the damage caused to agricultural production by animals, especially that this activity is the main source of subsistence and income for neighboring households. The social vulnerability process goes as such: First, crop raiding increases labor and brings about threats to health or education through increased time spent in guarding fields (Naughton-Treves 1997; Hill 2000, 2004; Gadd 2005; Osborn and Hill 2005; Ogra 2008); then, it affects farmers' livelihoods inducing economic and food insecurity (Kaswamila et al. 2007; Barirega et al. 2010; Hartter et al. 2011), sometimes leading households, in extreme cases, to abandon fields or villages (Naughton et al. 1999; Sitati et al. 2005; Treves et al. 2006).

Although the phenomenon of human–wildlife conflicts is the expression of the interaction between humans and wildlife, most studies to date have focused on either humans or wildlife, and very little studies approach the phenomenon from a holistic point of view (Fairet 2012). In Africa, several researches have been carried out on human–wildlife conflicts. Those who approach the problem from a biophysical perspective often deal with the damage aspects, the animals involved, and the environmental factors of human–wildlife conflicts (Kolowoski and Holekamp 2006; Kouao et al. 2018; Biset et al. 2019). As for research focusing on local communities, they often address the socio-economic impacts of the damage and attitudes toward wildlife. Some authors, such as Aust et al. (2009) and Rust and Marker (2013), are interested in this aspect of the question.

In Benin, a West African country that hosts the Pendjari Biosphere Reserve around which agricultural activities are practiced (Houinato and Sinsin 2000; Sogbohossou 2000), human–wildlife conflicts are a reality that has interested many researchers, such as the works of Sogbohossou et al. (2011, 2013, 2017) and Djagoun et al. (2017). Most of these works studied the biophysical aspects of the question, and only Tehou et al. (2018) and Efio et al. (2018) focused their work on local communities. The latter, respectively, assessed the economic impact of human–elephant conflicts on households and human–wildlife conflict management measures to curb crop raiding, and they concluded that such measures are not efficient.

Indeed, finding durable techniques to (partially) solve the human–wildlife crisis around the Pendjari Biosphere Reserve requires to take a closer look at the relationships between humans to their natural environment and at the personal representations of their environment (fauna). More specifically, the representations of local residents are underpinned by their level of sensitivity and vulnerability to human–wildlife conflicts. The less vulnerable they are, the more they will be tolerant to wildlife and the more successful conservation efforts will be.

5 Conclusion

This study of crop raiding around the Pendjari Biosphere Reserve reveals that cotton, maize, millet, and sorghum were the most damaged crops by wildlife. The main animals responsible for this destruction are the baboons, the warthogs, and the elephants. The impacts on local communities surrounding this protected area are economic and social, thus making these communities vulnerable.

We have seen that the economic damage is not trivial: Depending on the crop type, 22 to 30% of the annual production may be lost. This entails important losses valued at $95 to $312 for an average farmer. Brought back to an average-sized farm cultivating the four crops, the annual loss would reach $523, which is a very high amount in absolute value, considering the minimum wage in effect in Benin. To minimize those losses and reduce vulnerability, farmers set up various mitigation measures but research showed that their effectiveness is generally limited.

Despite a very abundant literature on human–wildlife conflicts, few studies have addressed the vulnerability of households. Assessing the vulnerabilities of local residents to human–wildlife interactions makes it possible to approach the question from a holistic perspective so as to develop solutions with the potential to ensure the sustainability of the social–ecological system as a whole.

References

Adams WM (2004) Against extinction: the story of conservation. Earthscan

Adams WM, Hutton J (2007) Parks, people and poverty: political ecology and biodiversity conservation. Conserv Soc 5(2):147–183

Ahouansou Montcho S, Lalèyè P, Linsenmair EK (2009) Lengthlength, length-weight relationships and condition factor of Nile perch, *Lates niloticus* (Linnaeus, 1762) in the Pendjari River, West Africa. Int J Biol Chem Sci 3(3):466–474

Aust P, Boyle B, Fergusson R, Culson T (2009) The impact of Nile Crocodile on rural livelihoods in Northestern Namibia. South African Wildl Res 39(1):57–69

Balme GA (2009) The conservation biology of a nominally protected leopard population. PhD thesis, University of KwaZulu-Natal, Westville, South Africa

Barirega A, Buyinza M, Kansiime F, Basuta-Isabirye G (2010) The effects of crop raidingon household food security in the Albertine Rift: a case study of Queen Elizabeth NationalPark, Western Uganda. Human Dimensions Wildl 15(1):45–54

Barua M, Bhagwat SA, Jadhav S (2013) The hidden dimensions of human–wildlife conflict: health impacts, opportunity and transaction costs. Biol Cons 157:309–316

Berkes F, Folke C, Colding J (1998) Linking social and ecological systems: management practices and social mechanisms for building resilience. Cambridge University Press

Biset A, Mengesha G, Girma Z (2019) Human–wildlife conflict in and around Borena Sayint National Park, northern Ethiopia. Human–Wildl Interact 13(1):111–124. www.digitalcommons.usu.edu/hwi

CENAGREF (2016) Réserve de Biosphère de la Pendjari: Plan d'Aménagement et de Gestion Participatif, 2016–2025. Programme d'Appui aux Parcs de l'Entente, Composante 2. Centre National de Gestion des Réserves de Faune, Bénin

Conover MR (2002) Resolving human-wildlife conflicts: the science of wildlife damage management. CRC Press, Boca Raton, FL

Delvingt W, Heymans J-C, Sinsin B (1989) Guide du Parc National de la Pendjari. CECA-CEE-CEEA, DFRN/MDR, Cotonou, Bénin

Djagoun AMS, Akpona H, Kassa B, Gichohi N, Muruthi P, Sinsin B (2017) Pachyderm 58:161–166

Djossa BA, Fahr J, Kalko EKV, Sinsin BA (2008) Shea fruits as key resources of flying foxes (Pteropodidae) in northern Benin, West Africa, and the effects of seed handling by bats on germination rates. Ecotropica 14:37–48

Dossou EM, Houessou LG, Lougbegnon TO, Codjia JTC (2019) Common hippopotamus-human conflicts in Ouémé River area in central Benin Republic. Int J Innov Appl Stud 25(2):638–644. ISSN: 2028-9324. http://www.ijias.issr-journals.org/

Efio S, Sogbohossou EA, Magnon ZY, Houinato MRB, Habiyaremye M, Sinsin BA, Tossou CR (2018) Human-wildlife conflicts and mitigation measures in Pendjari Biosphere Reserve, Northern Benin. Ann des Sci Agronomiques 22(1):15–31. http://www.ajol.info/index.php/asab

Fairet EMM (2012) Vulnerability to crop-raiding: an interdisciplinary investigation in Loango National Park, Gabon, Durham theses, Durham University. Available at Durham E-Theses Online. http://etheses.dur.ac.uk/6399/

Fisher M (2016) Whose conflict is it anyway? Mobilizing research to save lives. Oryx 50:377–378

Folke C, Carpenter SR, Walker B, Scheffer M, Chapin T, Rockstrom J (2010) Resilience thinking: integrating resilience, adaptability and transformability. Ecol Soc 15(4):20. [online] http://www.ecologyandsociety.org/vol15/iss4/art20/

Gadd ME (2005) Conservation outside of parks: attitudes of local people in Laikipia, Kenya. Environ Conserv 32(1):50–63

Hartter J, Goldman A, Southworth J (2011) Responses by households to resource scarcity and human–wildlife conflict: issues of fortress conservation and the surrounding agricultural landscape. J Nat Conserv 19(2):79–86

Hill CM (2000) Conflict of interest between people and baboons: crop raiding in Uganda. Int J Primatol 21(2):299–315

Hill CM (2004) Human dimensions of wildlife farmers' perspectives of conflict at the wildlife agriculture boundary: some lessons learned from African subsistence farmers. Human Dimension Wildl 9(1):279–286

Houinato M, Sinsin B (2000) La pression agro-pastorale sur la zone riveraine de Réserve de Biosphère de la Pendjari. Tropicultura 18(3):112–117

Kaswamila A, Russell S, McGibbon M (2007) Impacts of wildlife on household food security and income in Northeastern Tanzania. Hum Dimens Wildl 12(6):391–404

Kiansi Y (2011) Cogestion de la Réserve de Biosphère de la Pendjari : Approche concertée pour la conservation de la biodiversité et le développement économique local. Université d'Abomey-Calavi, Thèse de doctorat, p 275p
Kolowski JM, Holekamp KE (2006) Spatial, temporal, and physical characteristics of livestock depredations by large carnivores along a Kenyan reserve border. Biol Cons 128:529–541
Kouao ML, Bene J-CK, Koffi AD, Kouame BA, Kone I (2018) Caractérisation des dégâts provoqués par la faune sauvage à la périphérie de la Forêt des Marais Tanoe-Ehy au sud-est de la Côte d'Ivoire. Int J Biol Chem Sci 12(4):1717–1730
Kouton MD, Ahamidé B, Djagoun SC, Sinsin B (2019) Facteurs déterminants la disponibilité en eau de surface dans les réserves de faune en zone savanicole ouest africaine. Revue de Géographie du Bénin Université d'Abomey-Calavi (Bénin), Volume thématique, décembre 2019, pp. 192–216
Lamarque F, Anderson J, Fergusson R, Lagrange M, Osei-Owusu Y, Bakker L (2009) Human wildlife conflict in Africa. An overview of causes, consequences and management strategies. FAO technical report, 112p
Linnell JDC, Odden J, Mertens A (2012) Mitigation methods for conflict associated with carnivore depredation on livestock. In: Boitani L, Powell RA (eds) Carnivore ecology and conservation: a handbook of techniques. Oxford University Press, Oxford, UK, pp 314–332
Lokossou RS, Akouehou GS, Avononmadégbé ML, Orou MA (2018) Modes de gestion des terres dans la zone tampon de la réserve de biosphère de la Pendjari. J Appl Biosci 124:12433–12445. https://doi.org/10.4314/jab.v124i1.5
Madden F (2004) Creating coexistence between humans and wildlife: global perspectives on local efforts to address human–wildlife conflict. Hum Dimens Wildl 9:247–257
MEA (Millennium Ecosystem Assessment) (2005) Ecosystems and Human Wellbeing: Biodiversity Synthesis. World Resources Institute, Washington, DC
Mhuriro-Mashapa P, Mwakiwa E, Mashapa C (2018) Socio-economic impact of human-wildlife conflicts on agriculture based livelihood in the periphery of Save Valley Conservancy, Southern Zimbabwé. The J. Anim. Plant Sci. 28(3):2018
Nago SGA, Grell O, Sinsin B, Rödel MO (2006) The amphibian fauna of Pendjari National Park and surroundings, Northern Benin. Salamandra 422(3):93–108
Naughton-Treves L (1997) Farming the forest edge: vulnerable places and people around Kibale National Park, Uganda. Geographical Review 87(1):27–46
Naughton L, Rose R, Treves A (1999) The social dimensions of human-elephant conflict in Africa: a literature review and case studies from Uganda and Cameroon. African Elephant Specialist, Human-Elephant Task Conflict Task Force. IUCN, Gland, Switzerland
Nowell K, Jackson P (1996) Wild cats: status survey and conservation action plan. Report. World Conservation Union, Gland, Switzerland
Nsonsi F (2018) Les conflits homme-éléphant (Loxodonta cyclotis): un défi pour associer les communautés locales à la conservation de la faune. Tropicultura 36(3):531–538
Nyhus PJ (2016) Human-wildlife conflict and coexistence. Annu Rev Environ Resour 41:143–171
Ogra MV (2008) Human-wildlife conflict and gender in protected area borderlands: a case study of costs, perceptions, and vulnerabilities from Uttarakhand (Uttaranchal), India. Geoforum 39(3):1408–1422
Osborn FV, Hill CM (2005) Techniques to reduce crop loss: human and technical dimensions in Africa. In: Woodroffe R, Thirdgood S, Rabinovitz A (eds) People and wildlife: conflict or coexistence? Cambridge University Press, pp 72–85
Packer C, Ikanda D, Kissui B, Kushnir H (2005) Conservation biology: lion attacks on humans in Tanzania. Nature 436:927–928
Parker GE, Osborn FV, Hoare RE, Niskanen LS (2007) Human elephant conflict mitigation: a training course for community-based approaches in Africa. Participant's manual. Livingstone, Zambia, Elephant Pepper Development Trust and Nairobi, Kenya, IUCN Species Survival Commission, African Elephant Specialist Group, Human-Elephant Conflict Task Force
Perez E, Pacheco LF (2006) Damage by large mammals to subsistence crops within a protected area in a montane forest of Bolivia. Crop Prot 25:933–939

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol Econ 52:273–288

Redpath SM, Bhatia S, Young J (2015) Tilting at wildlife: reconsidering human–wildlife conflict. Oryx 49:222–225

Rust NA, Marker LL (2013) Cost of carnivore coexistence on communal and resettled land in Namibia. Environ Conserv 41(1):45–53. https://doi.org/10.1017/S0376892913000180

Sitati NW, Walpole MJ, Leader-Williams N (2005) Factors affecting susceptibility of farms to crop raiding by African elephants: using a predictive model to mitigate conflict. J Appl Ecol 42(6):1175–1182

Sogbohossou EA (2000) L'élevage des bovins autour des aires protégées et son impact sur la faune sauvage et son habitat: cas de la Zone Cynégétique de la Pendjari au Bénin. Mémoire d'Ingénieur Agronome, FSA/UNB, Bénin. 99p+annexes

Sogbohossou EA (2011) Lions of West Africa. Ecology of lion populations and human-lion conflicts in Pendjari Biosphere Reserve, North Benin. PhD thesis. University of Leiden, The Netherlands

Sogbohossou EA, De Iongh HH, Sinsin B, De Snoo GR, Funston PJ (2011) Human–carnivore conflict around Pendjari Biosphere Reserve, northern Benin. Oryx 45(4):569–578. http://journals.cambridge.org

Sogbohossou EA, Kassa BD, Aboubakar Z, Mahamane A (2013) Les conflits homme-girafe dans l'aire centrale de répartition de la girafe (Giraffa camelopardalis peralta linnaeus 1758) au Niger. Annales Des Sciences Agronomiques 17(2):107–119

Sogbohossou EA, Dansou PE, Djagoun CAMS (2017) Conflits hommes-hippopotames dans la Réserve Communautaire d'Adjamè ausud-ouest du Bénin. Bulletin de la Recherche Agronomique du Bénin (BRAB) Numéro 82–Décembre 2017, pp 22–31

Tehou AC, Mensah GA, Sinsin AB (2018) Impacts des fréquentations des troupeaux de Loxodonta africana dans les exploitations agricoles contigues à la Réserve de Biosphère de la Pendjari (Bénin). Ann des Sci Agronomiques 22(2):201–211. http://www.ajol.info/index.php/asab

Thirgood S, Woodroffe R, Rabinowitz A (2005) The impact of human–wildlife conflict on human lives and livelihoods. In: Woodroffe R, Thirgood S, Rabinowitz A (eds) People and wildlife: conflict or coexistence? Cambridge University Press, Cambridge, pp 13–26

Treves A, Wallace RB, Naughton-Treves L, Morales A (2006) Co-managing human-wildlife conflicts: a review. Hum Dimens Wildl 11(6):383–396

Weladji RB, Tchamba MN (2003) Conflict between people and protected areas within the Bénoué Wildlife Conservation Area, North Cameroon. Oryx 37:72–79

World Trade Organization (WTO) (2020) https://www.wto.org/english/tratop_e/agric_e/01_benin.pdf

MSc. Sylvain Efio is an Agro-Socio-Economist and Ph.D. student in Agronomics Sciences at Abomey-Calavi University, Benin and in Economics and Management at Université Saint-Louis, Belgium. He is a member of the Laboratory of Rural Sociology and Extension and of the Center for Research in Economics, Université Saint-Louis. His doctoral research falls within the field of Natural Resources Economics and Sociology and relates to "perceptions of risks and vulnerabilities of agricultural households to human-wildlife conflicts around Pendjari Biosphere Reserve in North Benin".

Dr. Ir. Etotépé A. Sogbohossou is an Agricultural Engineer with a Ph.D. in Natural Resources Management and Conservation. She is currently Associate Professor in Natural Resources Management and Wildlife Conservation and the Scientific Secretary of Doctoral Training in Natural Resources Management of the Faculty of Agronomic Sciences, University of Abomey-Calavi, Benin.

Dr. Yves Z. Magnon has a Ph.D. in Sociology and Anthropology. He is currently an Associate Professor at the School of Economics, Socio-Anthropology and Communication for Rural Development of the Faculty of Agronomics Sciences, University of Abomey-Calavi, Benin.

Dr. Bertrand Hamaide has a Ph.D. in Systems Analysis and Environmental Economics from the Johns Hopkins University (USA). He is a Full Professor of Economics at Université Saint-Louis, Brussels, Belgium. He is currently the Vice-Rector of the University after having served 6 years as a Dean of the Faculty of Economics, Social, Political and Communication Sciences.

Dr. Ir. Marcel R.B. Houinato is an Agricultural Engineer and has Ph.D. in Natural Resources Management and Conservation. He is currently a Full Professor in Natural Resources Management & Wildlife Conservation and the Head of the Doctoral School of Agronomic Sciences and Water, Abomey-Calavi University, Benin.

Dr. François M. Habiyaremye has a Ph.D. in Natural Resources Management and Conservation. His research is focused on ecology, botany, biodiversity and conservation, forest ecology, etc. He is currently affiliated to the Royal Belgian Institute of Natural Sciences, Brussels, Belgium.

Dr. Ir. Rigobert C. Tossou is an Agricultural Engineer with a Ph.D. in Rural Sociology and Extension. He is a Full Professor of Rural Sociology at the School of Economics, Socio-Anthropology and Communication for Rural Development of the Faculty of Agronomics Sciences, Abomey-Calavi University, Benin. He is currently the Head of Laboratory of Rural Sociology and Extension.

Dr. Ir. Brice A. Sinsin is an Agricultural Engineer with a Ph.D. in Natural Resources Management and Conservation. He is a Full Professor in Natural Resources Management and Wildlife Conservation. He was the Rector of the Abomey-Calavi University from 2011 to 2017, and currently the Head of the Laboratory of Applied Ecology.

Human Activities as a Potential Risk to the Sustenance of Barawa Forest Reserve in Katsina State, Northern Nigeria

Suleiman Iguda Ladan

Abstract This chapter examines human activities as potential risk to the sustenance of Barawa forest reserve, Katsina State, northern Nigeria. Data for the study were generated through direct observations on the forest reserve on the basis of three field visits and additional primary sourced data collected through the administration of a structured questionnaire. Results showed that numerous human activities have posed serious risks to the sustenance of the reserve. These include illegal cutting of trees, fires in the reserve set to burn tires or hunt animals, collection of laterites for building purposes, encroachment for building or farming activities, and overgrazing by domestic animals. The effects of such activities on the environment are various and include loss of wind breakers and increase in related environmental hazards. Governments in the past continue to take the necessary measures but their efficiency in ensuring the conservation and protection is questionable. This chapter recommends that strategies should be adopted to ensure resilience and viability of the reserve against human activities.

Keywords Forest reserve · Human activities · Nigeria · Potential risks · Sustenance

1 Introduction

According to the Global Assessment Report on Biodiversity and Ecosystem Services released in May 2019, scientists have warned that one million animal and plant species are at risk of extinction due to human activities within the next few decades with serious consequences, especially in the developing world (UN 2019).

According to Dagba et al. (2017), forests provide a wide variety of highly valuable ecological and social services, including the conservation of biological diversity, storage of carbon, conserving soil and water, provision of food and employment, enhancement of livelihoods, recycling of nutrients for crop production systems, and

S. I. Ladan (✉)
Department of Basic and Applied Sciences, Hassan Usman Katsina Polytechnic, Katsina, Katsina State, Nigeria
e-mail: suleimaniguda@yahoo.com; suleiguda@hukpoly.edu.ng

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_17

improvements of urban living conditions. Therefore, the creation of forest reserves is necessary as there are few forested areas of the world that remain untouched by human activities (Mannion 1991).

A forest reserve refers to a forest that has been accorded a certain level of protection against unauthorized usage by individuals and groups. Such reserves are usually protected under the laws of a particular country where it is situated, and certain activities such as tree cutting, hunting, and grazing are strictly prohibited by law (Morton 2014). Forest reserves are areas of forests that are designated and set aside government for the protection of trees planted or grown given their ecological benefits to the society, medicinal purposes or their potential in generating revenue from tourism and employment (Cumming et al. 2015).

In the USA, examples of forest reserves include Tongass National Forest in Alaska and Coconino National Forest in Arizona. In Ghana, examples of forest reserves include Asubima forest reserve and Krokosua hill Forest reserve (GFW 2020). In Nigeria, there are many areas of forests that were set aside as forest reserves in both southern and northern parts of the country. Recent studies have shown that the forest reserves are threatened by various human activities. One such studies is by Dagba et al. (2017) on Okokio forest reserve in Benue State Nigeria. The study revealed that urbanization, fuel wood collection, bush burning, logging, and land clearing were the major anthropogenic activities affecting sustainable forest management. Abdulzeez et al. (2018) studied Zamfara State forest reserves and found out that indiscriminate destruction of the forest for agriculture, encroachment by illegal timber, and fuel wood collectors and insecurity are responsible for the menace of deforestation.

Adamu (2019) studied Girei forest reserve, Adamawa State and the results revealed fuel wood extraction and over-cultivation as the main causes of deforestation. The study revealed that forest area reduced from 177.03 km^2 in 1987 to 75.98 km^2 in 2015 (Adamu 2019). Wada et al. (2019) studied Duddurun Gaya forest reserve in Kano State and indicated a massive illegal cutting of trees, which accounting for 22.66% and 43.08% of vegetation affecting a total size of 41.77 and 93.70 km. In a study by Ladan (2019), in the Runka forest reserve, Katsina State, the cutting of trees for fuel wood, expansion of farmlands into the forests, hunting and poaching activities, dryness of water lodges and reservoirs, and inadequate protection of the forest reserve were considered as responsible for the loss of the forest's faunal diversity.

These studies are similar to the present study as they all focus on human activities threatening the sustenance of forest reserves in different parts of Nigeria, but none of them focused on the Barawa forest reserve located in Batagarawa Local Government Area (LGA) of Katsina State. This chapter examines the above in the context of the sustenance of Barawa forest reserve of Katsina State, northern Nigeria. The objectives are to:

- Explain the background history of the Barawa forest reserve;
- Describe the nature and composition of the Barawa forest reserve;
- Explain human activities as elements of potential risk to the sustenance of Barawa forest reserve;

- Highlight impacts of the human activities on the forest reserve to Barawa village and surrounding settlements;
- Highlight the efforts of past and present governments to sustain the forest reserve; and
- Recommend measures toward ensuring viability and resilience of the forest reserve.

2 Study Area

Barawa is the name of a village settlement in Batagarawa LGA of Katsina State longitude 12°54′0° North of the equator and latitude 7°25′0° east of Greenwich meridian (Fig. 1). Barawa is situated 12 km southwest of Katsina, the capital of Katsina State along the Katsina to Batsari road. The village is administratively under Batagarawa LGA of Katsina State, one of the seven villages that have village heads and falls under Ajiwa district of the LGA (Bawa 2012). The occupation of the inhabitants of the village is mainly farming, animal rearing, trading, and some of the people are employed at the Afdin Construction Limited Quarry site located outside the village. The whole Batagarawa LGA has a population of 189,059 people comprising 96,693 males and 92,366 females, as per the 2006 National Population Census (Bawa 2012).

In terms of physical setting, the relief of the village is part of the high plains of Hausa land of northern Nigeria. The drainage consists of a few streams that dry up during the summer and a large water pond located outside the village that serves as a source of water supply for domestic purposes. The climatic type is tropical continental characterized by long dry season over September to April, and short wet season over May to August every year. The annual average rainfall is about 700 mm and maximum day temperature of about 38 °C is common in April and May before the onset of the rains (Umar et al. 2018). The vegetation type is Sudan savannah that is characterized by short scattered trees, shrubs, and grasses. In some areas, these trees grow in close formation to form a forest like the Barawa forest reserve. Human activities have, however, affected most of the vegetation cover in Barawa and the surrounding villages of Batagarawa LGA.

3 Materials and Method

3.1 Materials Used in the Study

One of the materials used for the study is a map of the study area, Batagarawa LGA, which was drawn at the cartography unit of the Department of Geography Umaru Musa Yar'adua University Katsina, Katsina State. The map is used to describe the specific study area Barawa, the forest reserve, and the surrounding village settlements that engage in different activities in the forest reserve. This map also has two insert

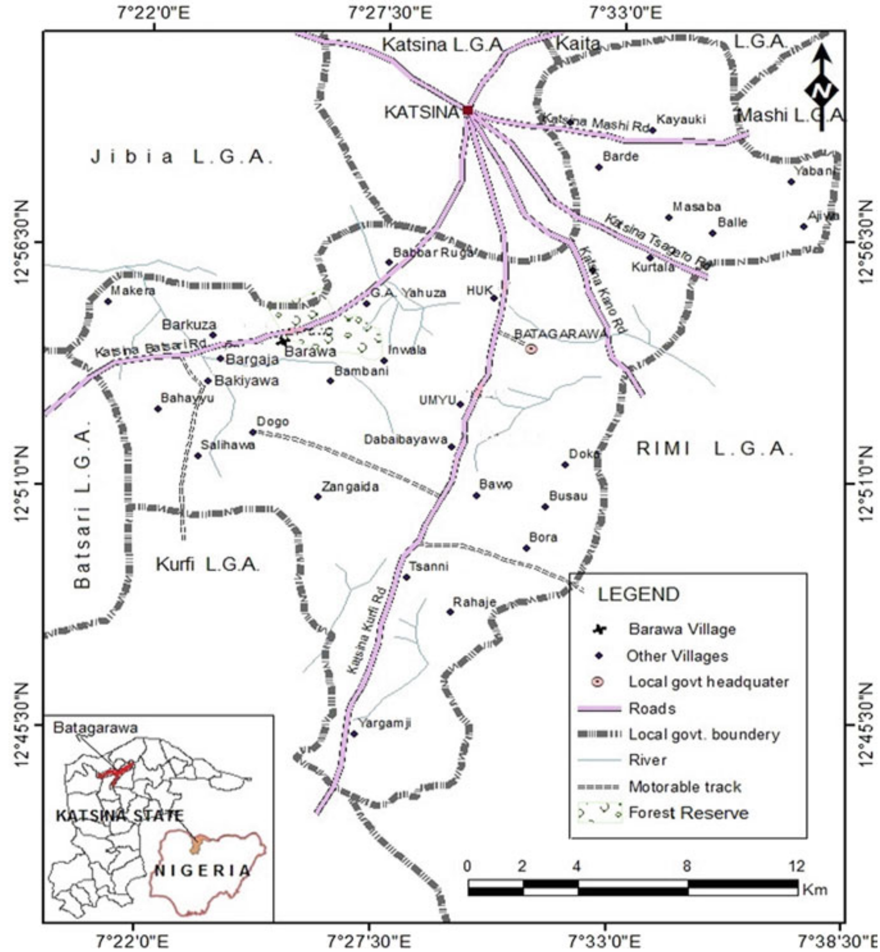


Fig. 1 Map of the study area. *Source* Geography Dept. UMYU, 2019

maps of Katsina State and Nigeria as a country to further describe the study area for readers. Another material used for the study is a WX_3 Tecno phone to snap pictures of the forest reserve, fuel wood collected from the reserve, and fuel wood carts that were confiscated from fuel wood collectors. These pictures were included into the study to give a visual impression of the risks posed by human activities to the forest reserve.

3.2 Methods of Data Collection

Direct observational technique was used to take note of the location, condition, and the risk posed by human activities to the sustenance of the forest reserve. These observations were made during three field visits to the forest reserve, Barawa and Bakiyawa villages on May 4, 2019, February 8, 2020, and April 9, 2020. During the first field visit, the village Head of Barawa served as a research assistant agreed to go around the forest reserve to assess the current situation. The second field visit on February 8, 2020, was held at Bakiyawa with the assistance of a colleague from Hassan Usman Katsina Polytechnic, Katsina. The third visit on April 9, 2020, was held at Barawa with the Village Head assigning a primary school teacher and a local farmer the responsibility to serve as research assistants.

Additional data were collected using a structured questionnaire that was administered on the people who were seen exploiting the reserve and residents of the surrounding villages who know the forest reserve and the activities that were carried out in the research. Ten questionnaires were administered on the residents of Barawa, the main village where the reserve is located and 5 questionnaires each on other seven villages and Katsina town. These seven villages are Bargaja, Barkuza, Bakiyawa, Bambami, Babbar Ruga, Yar Shanya, and Garin Alhaji Yahuza. These gave a total of 50 questionnaires administered to collect data for the study.

These settlements, including Barawa, are within 2–12 km distance to the reserve, and they all carry out various activities such as fuel wood collection, farming, and excavation of laterite at the forest reserve. These settlements, with the number of questionnaires administered and the approximate distance to the forest reserve, are presented in Table 1.

The questionnaires consist of two sections A and B: The section A contains questions on the demographic characteristics of the respondents, and the section B contains the main questions covering the background history of the reserve, human

Table 1 Settlements where questionnaires were administered and their distance from the forest reserve

S/N	Name of settlement	No. of questionnaires administered	Approximate distance to the forest reserve (km)
1	Barawa	10	2
2	Bambami	5	2
3	Bargaja	5	4.5
4	Barkuza	5	4.5
5	Bakiyawa	5	8.0
6	Babbar Ruga	5	10.0
7	Garin Alhaji Yahuza	5	8.0
8	Katsina	5	12.0
9	Yar Shanya	5	11

activities, impacts of human activities, efforts of past and present governments to sustain the reserve, and suggestions to ensure viability and resilience. These primary sources of data were complemented with secondary sourced data collected through desk research from peer-reviewed journal articles, conference papers, government environmental reports, historical sketches, and Internet sourced materials. The data collected from both primary and secondary sources were analyzed through descriptive statistics in form of percentages, means, averages, and tabulations.

4 Results and Discussion

4.1 Demographic Characteristics of the Respondents

The demographic characteristics of the respondents from the nine settlements showed that the majority (80%) are males while only a minority (20%) are females. This is based on the tradition in the study area where males are found outdoors and engage more in occupations that are associated with forests. In terms of age range, those in the age group of 25–29 constitute 30% the highest among the groups, 56% are married while 44% are not married and therefore single. Despite being not married this group goes to the forest reserve to find a source of livelihood due to few occupations in the rural areas. The twenty-eight (28) respondents that are married have different number of children in their families. The highest among them are those with 10–14 children which constitute 42.85% among them. Among those that are married, the number of wives differs, a majority were (60.71%) married to two wives while the others were married to one to three wives. Seventy percent (70%) had no formal education other than Quranic education as they reside mostly in rural areas where the level of literacy is low and as such even the questionnaire had to be translated into the local language of Hausa. The remaining respondents (30%) are the ones that had received primary, secondary, and tertiary level education (Table 2). The occupational status of respondents showed that 40.00% engaged in farming and rearing of domestic animals. Thirty percent (30%) are engaged in fuel wood collection for sale from the Barawa forest reserve and other areas, and 10% are not employed and therefore depend on the Barawa forest reserve and its resources for their source of livelihoods. Twelve percent of the respondents are civil servants, five of who work at the Hassan Usman Katsina Polytechnic, Katsina, and one is the Zonal Forest Conservation and Protection Officer who were met on duty at the reserve during the third field visit to Barawa village on April 9, 2020. Four percent engage in trading activities that involved visiting weekly markets across the state. The demographic characteristics of the respondents can be seen in Table 2.

Table 2 Demographic characteristics of the respondents

Characteristics	Frequency	Percentage (%)
Gender		
Male	40	80.00
Female	10	20.00
Age group		
15–19	10	20.00
25–29	15	30.00
35–39	08	16.00
45–49	04	08.00
50–54	08	16.00
60 years and above	05	10.00
Marital status		
Married	28	56.00
Single	22	44.00
No. of wives for those married		
One	06	21.42
Two	17	60.71
Three	05	17.85
Four	–	–
No. of children for those married		
1–4	05	17.85
5–9	08	28.57
10–14	12	42.85
15–19	03	10.71
Educational qualification		
No formal education	35	70.00
Primary school education	07	14.00
Secondary school education	04	08.00
Tertiary level education	04	08.00
Occupational status		
Farming and animal rearing	20	40.00
Fuel wood collection	15	30.00
Civil service	06	12.00
Unemployed	05	10.00
Trading	04	08.00

4.2 Background History of Barawa Forest Reserve

Barawa forest reserve has a long history as narrated by 10% of the respondents who are aged 60 years and above. According to them, the area where the reserve is located presently used to be farmlands of the people of Barawa, Bakiyawa, and other surrounding villages. Large parts of the forest reserve consisted of *Gandu* in Hausa language which means large farmlands. Eight *Gandus* were named, namely Gonar Kufar Rumfuna, Adda, Kurmau, Bebe, Jaji, Baram Malam, Yada Mara, and Saura Maigan. The owners of these eight large farmlands were directed by the then Emir of Katsina Usman Nagogo (1944–1981) to stop farming as the land area has been declared a forest reserve in the year 1950. Based on this directive, the owners of the eight large farms decided to leave Barawa and migrate to other areas. The Emir used to come every year to the area for farming and hunting expedition. The objectives of establishing the forest reserve by the British colonial administration were to stem the tide of desertification and halt the encroachment of Sahara Desert (Babsal and Co. Limited 1998).

Due to lack of farming activities in the reserve, many trees started to grow naturally as more rains were received at that time. By the year 1970, the Katsina topographical map sheet 34 NW first edition drawn by Federal Surveys showed the Barawa forest reserve as a flourishing reserve with dense collection of trees (Ladan 2013). Local people of the area fear going through the forest due to its high tree density making it difficult to cut trees. The wild animals found in the forest at that time include seasonal elephants (*Loxodonta africana*), lions (*Panthera leo*), hyenas (*Crocuta crocuta*), monkeys (*Chlorocebus pygerythrus*), foxes (*Vulpes vulpes*), gazelles (*Eudorcas thomsoni*), and many more including the lower animals that remain presently.

By the year 1973, a 44 km tarred road was constructed from Katsina to Batsari through Barawa forest reserve, which resulted in clearing of trees and other forms of vegetation. Also, the road construction activities opened up the forest to deforestation with people cutting trees and transporting them to Katsina City for use as fuel wood. In 1977, a heat wave from underground known as *Busau* in the local Hausa language further led to the drying and death of many trees in the forest reserve.

By the year 2000, four wealthy and influential men from Katsina City came with their laborers and started cutting trees for the purpose of creating large farmlands within the forest reserve (Ladan 2000). The planting of crops has started but the local people of Barawa and Bakiyawa villages revolted, blocking the Katsina-Batsari road as a protest. A petition was written to the Chairman Batagarawa LGA with the case later taken to court, and it took five years after which the people won and those who encroached into the forest reserve were ordered to vacate the area.

By the years 2008–09, a section of the reserve close to the main road was allocated to Africa International Television for the construction of Ray Power radio station. This further led to the clearing of about 20 ha of an area covered with trees and undergrowth. At the beginning of the second tenure of the administration of Governor Ibrahim Shehu Shema (2011–2015), a waste dump site measuring 200 by 200 m was constructed deep into the reserve for waste dumping by the State Environmental Protection Agency (SEPA). Also, a private poultry farmer was allocated an area of land in the forest reserve for the dumping of poultry wastes. Furthermore, in 2011, an area of land in the forest reserve was allocated for the construction of a Federal University. An untarred road was built for access to the site, after which the university project moved to Dutsinma in Dutsinma LGA.

From the foregoing history, it can be observed that the Barawa forest reserve is one of the few areas where the government allocates land for various construction projects without concern for the ecological importance of the forest reserve (Ladan 2013). Therefore, on March 9, 2020, three caterpillar bulldozers came to the reserve and started clearing a large land area of about 100 ha beside the Ray Power radio station. Three boreholes were constructed, and it was later learned that the cleared area of land is for the construction of coronavirus isolation center. However, after the visit of the Governor of the State, it was announced that the hospital project has been moved to a ward inside Orthopedic Hospital Katsina along Dutsinma road. According to respondents from Barawa village, this large-scale clearance of the forest reserve sent a wrong signal to some people, especially the youths and middle-aged from Katsina town who came in large numbers to uproot and cut the remaining shrubs and trees. During the last field visit, some of these people were seen with sacks containing the uprooted shrubs and trees loading on J5 buses, tricycles, and motorcycles for transportation to Katsina town for sale. These people who cut the trees have even threatened to attack the forest conservation and protection officer from the Department of Forestry, Ministry of Agriculture.

The local people of Barawa village are expressing fear that this area of land cleared for the hospital project may be allocated to rich persons for the benefit of themselves and their children and to the detriment of the local people whose grandfathers once owned the land area. Again, on April 3, 2020, officials from Nigerian Security and Civil Defense Corps (NSCDC) came to Barawa to inform the Village Head that they have been granted permission to use the land area on the other side of the Ray Power radio station for the building of a housing estate for members of the corps.

4.3 Nature and Composition of Barawa Forest Reserve

The Barawa forest reserve covers an aerial extent of 19 square miles or 30.4 km^2 outside Barawa village along Katsina-Batsari road (Fig. 1). The reserve is surrounded by villages such as Barawa, Bambami, Inwala, Garin Alhaji Yahuza, and others that are within 2–10 km distance, which makes it easy for people to come in to carry out various activities. The reserve is under the Federal Ministry of Environment supported forest reserve management program. But the protection and conservation of the reserve are carried out by the Department of Forestry of Ministry of Agriculture and Natural Resources, Katsina State.

The reserve is of a mixed type consisting of different tree species, such as *Combretum micranthum, Guiera senegalensis, Acacia seyel, Hyphaene thabaica,* *Hauhinia rufenscens, Acacia nilotica,* and *Azadirachta indica. Combretum micranthum* called *Geza* in the local Hausa language is the dominant species in many areas. There is a large plantation of *A. indica* that was planted in 2005 by British American Tobacco Company (BATC) located in the southwestern part near Jibia LGA boundary.

The animal species that are presently found in the reserve include mostly lower animals and few reptiles. These include rats, rodents, rabbits, squirrels, wild guinea fowls, fox, porcupines, snakes, scorpions, etc. Animals present in the forest reserve have attracted a group of hunters with their hunting dogs that came for hunting from surrounding villages in the morning or evening of every Wednesday.

The spate of insecurity involving banditry, cattle rustling, and kidnapping that has affected the Rugu forest in Safana and Batsari LGAs has led people from 2010 to date to put pressure on the Barawa forest reserve. This is because some people have stopped going to the Rugu forest and turned to the Barawa forest reserve to cut trees for fuel wood. The result is that the forest reserve looks open with very few trees and lots of shrubs such as *C. micranthum and G. senegalensis* whose stumps are uprooted by fuel wood collections. Furthermore, years of excavation of kaolin have created big gullies near the road leading to Barawa from Katsina. In other areas of the reserve, large hollows and pits resulted from the excavation of laterite using tippers by some construction firms.

4.4 Human Activities Generating Potential Risk for the Sustenance of Barawa Forest Reserve

Based on the questionnaire administered for data collection, numerous human activities are posing serious risks to the sustenance of the Barawa forest reserve had been identified. These are presented in the following.

Encroachment for Farming Activities

Historically, this is the first major human activity that poses risk to the sustenance of the forest reserve. The clearance of trees and other forms of vegetation by the three large-scale farmers from Katsina created a large empty space within the forest reserve not filled with trees at present. At the edge of the reserve too, people from the surrounding villages have for some years been encroaching into the reserve to increase the size of their farmlands or create new farms in response to population growth. The encroachment into forest reserve is a common feature in most forest reserves in Katsina State. A study by Ladan (2013) showed that the Nasarawa forest reserve in the neighboring Jibia LGA was encroached upon by some individuals for the purpose of farming and settlement.

Fig. 2 Ray Power radio station building in Barawa forest reserve

Allocation of Forest Land for Construction Purposes

The government allocates land area in the forest for the purpose of building construction. The Ray Power radio station in 2008–09, untarred road for building a Federal University in 2011, the building of SEPA waste dump site and private poultry farm wastes dump in 2012, the clearing of land for coronavirus treatment hospital, and the recent plan to build housing units for NSCDC. There is also a beacon showing an area in the forest being allocated to Sonado Metal Works Nigeria Limited. These buildings and planned constructions have led to the clearance of large areas of vegetation. They also open up spaces and encourage fuel wood cutters to come into the forest to cut and uproot the remaining vegetation that stabilizes the soil. Figure 2 shows the Ray Power radio station building inside the forest reserve.

Illegal Cutting of Trees for Fuel Wood

This is among the human activities that pose serious threat to the sustenance of the forest reserve. A large percentage of the people in Barawa and the surrounding villages use trees as a source of fuel wood to meet cooking energy needs. The demographic characteristics of the respondents showed that the occupation of 32% of the respondents is fuel wood extraction and clearly indicates their reliance on the forest reserve as a source of livelihoods. The prevailing economic hardships that manifest in increasing levels of poverty and unemployment have further pushed people to cut trees in the forest reserve. The recent clearance of part of the reserve for construction purposes has also led to an increasing rush into the reserve to illegally

Fig. 3 A resident of Garin Alhaji Yahuza transporting cut trees out of the forest reserve

cut trees even up to the roots! Fig. 3 shows one of the residents of Garin Alhaji Yahuza transporting bunches of cut trees out of the forest reserve.

Excavation of Laterite and Kaolin

This is another human activity that is posing serious risk to the sustenance of the forest reserve. This act involves digging the ground to collect laterite that is transported by tipper vehicles out of the reserve to Katsina town. This activity leads to the clearance of vegetation and also the creation of hollows that can expand to create gullies rendering the land area useless. At one time, there was disagreement between the excavators and the local government and it was resolved that they will be paying the sum of N20,000 for the excavation any day the activity is carried out. Besides this excavation of laterites, the local people around the forest reserve also excavate kaolin, which is used locally for plastering of rooms in their houses. This excavation also has seriously affected the forest reserves as large gullies have been created, which are even threatening part of the Katsina to Batsari road.

Setting Fire in the Reserve

This is the activity whereby some people brought old and used tires in the forest reserve and then set them on fire. After the complete burning of tires, the wires are collected for sale. The burnings affect the trees and other forms of vegetation in the forest. During the first field visit to the reserve, some of these burning spots were seen in the reserve. In addition to this, there are also some people who engage in bush burning in order to force some animals such as rats, rodents, and rabbits to come out of the place they are hiding. These burnings affect the forest reserve by

Fig. 4 A signpost erected at the Barawa forest reserve warning people about certain prohibited activities

eliminating trees and shrubs. People are warned against such degradation through signposts erected in the forest reserve (Fig. 4).

Illegal Grazing by Domestic Animals

The people of Barawa and surrounding villages practice free ranching where domestic animals were released into the forest reserve to graze on any available form of vegetation. This practice does not allow plants to re-germinate, particularly during the rainy season when some plants have however started to germinate again. According to the village head of Barawa in the year 2018, Batagarawa LGA planted tree seedlings in the forest reserve but they were destroyed by cows and goats due to lack of fencing. A study by Badamasi (2014) noted that the dense woodland of Falgore Game Reserve Kano State, has turned to very open woodland within three decades and one of the factors responsible is grazing of domestic animals within the reserve.

5 Impacts of Human Activities in Barawa Forest Reserve

Based on the foregoing discussions, it can be observed that several human activities posed serious risks to the sustenance of Barawa forest reserve. The impacts of such activities are highlighted below:

- Wind erosion occurs as a result of the rampant deforestation given that the soil is presently covered with scanty vegetation cover. It is severe during the dry season blowing soil particles from the reserve toward the villages such as Barawa, Bargaja, Barkuza, and Bakiyawa.
- Winds blowing at high velocity due to the absence of vegetation cover affect the well-being of people. According to the village head, during the dry or rainy season

a person cannot look toward the eastern direction due to high winds affecting the eyes and other organs of the body.

- Soil erosion is occurring at a very fast rate as a result of the scanty vegetation cover arising from human activities such as cutting of trees for fuel wood. The excavation of laterite and kaolin in particular has led to the creation of gullies along the Katsina to Batsari road few kilometers to Barawa village. If this is not prevented, gullies will cut off part of the road disrupting transport.
- The excavations have also rendered some of the land area of the forest reserve derelict. This damage is due to the creation of hollows and gullies and it cannot be put to any productive use. Villagers also fear that these hollows can be used as hideout by criminals or bandits before launching any operation or attack on the surrounding villages.
- Wild animals that once used the forest reserve as their habitat have presently migrated to the Rugu forest and other forest areas within and outside Katsina State. The wild animals have been lost due to large-scale deforestation of the reserve and scarcity of water supply.
- Large-scale deforestation of the forest reserve has led to a drastic reduction of medicinal plants. In Nigeria, some rural communities, like Barawa and surrounding villages, are dependent on traditional medicine that uses the vegetation as a raw material. Such vegetation has been largely lost by the people around the reserve (Kankara et al. 2018).

6 Measures Adopted to Sustain the Forest Reserve

Several measures were adopted by the past and present governments in order to sustain the forest reserve. These measures are outlined below:

- Demarcating the area of the reserve to prevent encroachment by people. This is done using beacons to demarcate the edge of the reserve, thereby separating it from the people's farmlands and village buildings.
- Signposts have been erected in different parts of the reserve warning people to desist from illegal cutting of trees, setting of fire, laterite collection, and encroachment into government forest reserves as prohibited actions (Fig. 4). These warnings are written not only in English but also in local Hausa language for the benefit of the local people.
- The Permanent Secretary Ministry of Lands and Surveys issue announcements on the State Radio Service Katsina warning people to stop encroachment into Barawa forest reserve. This is important as it is the only forest reserve that remains within 15 km from Katsina urban area.
- In 2005, during the administration of the then Governor of Katsina State Alhaji Umaru Musa Yar'adua, a private company called British American Tobacco Company (BATC) planted thousands neem trees (*A. indica*) in order to improve the condition of the reserve due to the deforestation by large-scale farmers.

- In 2008, Batagarawa LGA carried out that year's Tree Planting Campaign by planning many tree seedlings in the Barawa forest reserve. However, the lack of protection materials, such as fencing wire and protective baskets, makes it difficult for the planted trees to grow and survive.
- From 2007 to 2015, the state government has employed two forest guards to guard the neem tree plantation established by BATC. These guards work through morning and evening sessions and were paid on a monthly basis. They assisted in sustaining the plantation even though they withdrew their services recently when they were not paid.
- The Department of Forestry through the Zonal Forest Office has been trying to ensure the protection and conservation of the Barawa forest reserve through daily patrol to keep away those who uproot the remaining trees. In one instance, the fuel wood collectors attempted to attack the forest officer and his men after confiscating sacks of uprooted trees and a locally made cart but the police intervened to chase them away (Fig. 5).
- The Village Head of Barawa has been trying to discourage people from cutting trees in the reserve. He does this by appealing to those he saw with bunches of trees to desist from cutting trees and asking them to try to find an alternative sustainable occupation.
- The European Union (EU) grant project in collaboration with the Energy Centre of Umaru Musa Yar'adua University Katsina has brought tree seedlings to the people of Barawa to plant them in the reserve. The project also trained farmers on nursery practices, agro forestry, and fuel wood conservation in five LGAs of Katsina State including Batagarawa (Sardauna 2019).
- Batagarawa LGA has from time to time been giving tree seedlings, including neem tree (*A. indica*), to the people of the surrounding villages in order to plant

Fig. 5 Sacks of uprooted trees and locally made cart confiscated from fuel wood collectors by Katsina Zonal Forest Officer

them in the reserve to assist in ensuring its sustenance. In addition, according to the respondents, some of the concerned people from the surrounding villages came up with the decision that nobody should uproot any of the remaining trees in the forest reserve.

7 Strategies for Ensuring Resilience and Viability

Forest reserve resilience refers to the capacity to recover quickly from difficult situations that are facing the reserve. Forest reserve viability, on the other hand, indicates the ability of the reserve to withstand from anthropogenic disturbances to persist over long periods of time (CGW 2020). The Barawa forest reserve has shown elements of resilience and viability over the years since its establishment in 1950 as it persisted up to the present time (2020). However, the following strategies are recommended in order to ensure resilience and viability of the Barawa forest reserve.

- The state government should henceforth desist from the practice of allocating land for building purposes in the Barawa forest reserve in order to sustain it. Once this is done, the people will have the feeling that it is still a reserved forest that should not be encroached upon for any purpose.
- The State and Local Government should join hands to ensure that excavation of laterite in the forest reserve is regulated so that it does not further harm the forest reserve. A land reclamation plan should be planned in order to reclaim the deep gullies created by kaolin excavation due to the local people in the reserve.
- The state government should enact strong laws against encroachment into the forest reserve for farming, cutting of trees, and creation of settlements. Once these laws are enacted, they should be publicized to reach the people and also enforced by competent authorities.
- The Zonal Forest Officer should continue the regular patrol of the Barawa forest reserve to halt the recent rush by those who cut and uproot trees. The Zonal Officer with his team should be given police escort in view of the threats posed by the tree cutters who are becoming aggressive.
- The State Department of Forestry should be given the permission to employ forest guards in order to guard the neem tree plantation at the forest reserve. Also, once they are employed, they should be paid regularly to enable them discharge their duties effectively.
- The setting of fire in order to burn tires or as a method of hunting wild animals should be discouraged through public enlightenment programs on the radio that will show the negative impacts of such practices on the forest ecosystem.
- The state government and Batagarawa LGA should launch a reforestation program in order to reforest the 100 ha of land that was cleared for the Coronavirus treatment hospital. This is important in order to stress that the area is still a forest reserve that needs to be forested.
- There is an urgent need to control overgrazing of domestic animals. This can be done through the education of people on the need to rear their animals in confined

areas. Any animal found grazing in the forest reserve should be confiscated until the owner come and explain the reason for allowing the animal to roam in the reserve.

- The state government through the Department of Forestry should give traditional rulers the power to oversee the protection of the reserves in their domains. The Village Head of Barawa is indeed trying to protect the reserve, but his authority and power should be reinforced to guarantee the efficiency of his interventions.

8 Conclusion

The Barawa forest reserve located in Batagarawa LGA of Katsina State, northern Nigeria, is one of the largest forest reserves in Katsina State. The reserve is important in view of its location in the northern parts of Katsina State threatened by the advancing desertification and encroachment of the Sahara Desert from neighboring Niger Republic. This threat indeed calls for the urgent need to sustain the forest reserve to perform its ecological functions. However, from the year 2000 to date, various human activities have posed risks to the sustenance of the forest reserve. These activities include encroachment for farming activities, allocation of forest land for construction purposes, illegal felling of trees for fuel wood among others. The human activities have negative impacts on the forest reserve. Governments have adopted various measures to sustain the reserve in the past and present. The strategies outlined in this chapter should be adopted to ensure resilience and viability of the forest reserve.

Acknowledgements The Author wishes to express gratitude for the assistance in data collection by the Village Head of Barawa Alhaji Aminu Usman Dangaladiman Barawa, Batagarawa LGA Katsina State, Nigeria.

References

Abdulzeez A, Ibrahim A, Shinkafi AM (2018) An examination of the socio-environmental effects of deforestation in Zamfara forest reserves. Federal University Dutsinma (FUDMA) J Sci 2(1):99–107

Adamu S (2019) Remote sensing and GIS application for forest reserve monitoring and prediction: a case study of Gerie forest reserve, Adamawa State. Federal University Dutsinma (FUDMA) J Sci 3(3):85–94

Babsal and Co. Limited (1998) Katsina state environmental action plan final report. Federal Environmental Protection Agency (FEPA) Ikeja, Lagos

Badamasi MM (2014) Vegetation and forestry. In: Tanko AI, Momale SB (eds) Kano Environment, Society and Development London Adonis and Abbey Publishers Limited

Bawa MG (2012) Katsina state pictorial and historical sketches. The First Twenty Five Years (1987–2012). Katsina Government Printer

Conservation Gateway (CGW) (2020) Viability in conservation. Retrieved from www.conservationgareway.org/viability

Cumming GS, Allen CR, Ban NC, Briggs D, Biggs HC, Cumming DH, Mathevet R (2015) Understanding protected area resilience: a multi-scale, social ecological approach. Ecol Appl 25(2):299–319

Dagba BI, Sambe LN, Adisa JE (2017) Effects of human activities on Okokio Forest Reserve in Benue State, Nigeria. Asian J Environ Ecol 3(1):1–11

Global Forest Watch (GFW) (2020) Forest reserves/global forest watch open data portal. https://data.globalforestwatch.org/datasets/fbf178be08c74d14b0e2d0cbb0382118_89

Kankara SS, Isah AB, Bello A, Ahmed A, Lawal A (2018) Medicinal plants used for the management of hepatic ailments in Katsina State. Niger J Med Plants Res 2(24):375–386

Ladan UB (2000) Batagarawa Local Government Chairman please save our soul. A petition submitted to Batagarawa Local Government Council Chairman 22nd May, 2000

Ladan SI (2013) An appraisal of the status and consequences of encroaching into forest reserves in Katsina Urban Environment Katsina State. Danmarna Int Multi Stud 5(1):91–101

Ladan SI (2019) Restoring faunal diversity of Runka Forest Reserve Safana Local Government Area, Katsina State Nigeria. In: 2nd international congress on geographical education, Osmangazi University, Eskisehir Turkey

Mannion AM (1991) Global environmental change: a natural and cultural environmental history. Essex England Longman Scientific & Technical

Morton A (2014) Six important roles forest reserves play in the lives of the citizens. https://virtualkollage.com/2018/08/six-important-roles-forest-reserves-play-in-the-lives-of-citizens

Sardauna F (2019) EU, Varsity Train 8,460 on agroforestry. www.independent.ng/eu-Katsina-varsity-trains-8,460-on-agroforestry

Umar NK, Sulaiman AM, Giwa SM, Sulaiman AY (2018) Spatio-temporal analysis of urban expansion in Katsina Local Government Area, Katsina State. Sokoto J Soc Sci 8(2):95–106

United Nations (UN) (2019) UN report: nature's dangerous decline—unprecedented. www.un.org>sustainabledevelopment>blog>201905

Wada AF, Umar AF, Musa BU, Tasi'u M, Bilyaminu H, Mubarak M, Ibrahim MI, Abubakar A (2019) Assessment of deforestation level in some selected forests in Nigeria: a case study of Duddurun Gaya Forest Reserve, Gaya Local Government Kano State, Nigeria. Direct Res J Public Health Environ Technol 4(1):1–7

Mr. Suleiman Iguda Ladan is presently a Chief Lecturer at the Department of Basic and Applied Sciences, Hassan Usman Katsina Polytechnic, Katsina State. He has an M.Sc. in Land Resources (Development). He is a seasoned paper presenter at national and international conferences. His areas of research cover the Agricultural Geography, Bio-geography, Environmental Management, Gender and Security Studies, Transport, Tourism and Urban studies. He is an Academic Editor for the Asian Journal of Geographical Research, one of the Science Domain International journals based online. He is a member of the Association of Nigerian Geographers, Nigerian Environmental Society and Asia Pacific Chemical Biological and Environmental Engineering Society.

Non-timber Forest Product Income: What Implications for Social Safety-Nets in Afaka Forest Reserve Communities, Kaduna-Nigeria?

John E. Ochi and Ezekiel Y. Zaman

Abstract The analysis of non-timber forest products (NTFPs) in social safety-nets context is a paradigm shift to focusing on the demand side of forest products as repository for providing ecological services to society, including food and energy security, medicines, raw materials, and platforms for protecting the cultural heritage as well as leveraging on safety-nets for poverty alleviation in the communities. In this approach, NTFP income forms the basis for constructing the income inequalities for the modelled occupations among the two groups of NTFP collectors, namely; only-NTFP collection, and NTFP collection with other economic activities.

Keywords Non-timber forest products · Income inequality · Gini index · Environment and social protection

1 Introduction

The poorest and most vulnerable people live in communities contiguous to forests to make a living from the forests. In other word, forests contribute significantly to the livelihood of people living in extreme poverty. Unprotected forests and/or forest resources are the bane of escalating poverty among this group of people around the world, especially in low and middle income countries (de Préneuf 2013).

There is a preponderance of non-timber forest products (NTFPs) across Nigeria, ranging from varieties of mushrooms, snails, large and small animals in the south to rodents, honey, and large animals in the north, which can be found in various types of forest across the country, including the lowland rainforests, the more humid coastal mangrove, fresh water swamp and riparian forest in the south, and savannah woodlands in the drier middle belt and northern Sudan and guinea savannah vegetation, including the montane forests in the north (USAID 2008; Igu et al. 2017).

J. E. Ochi (✉)
Department of Agricultural Economics, Abubakar Tafawa Balewa University, Bauchi, Nigeria
e-mail: eribaochi@gmail.com

E. Y. Zaman
Forest Research Institute of Nigeria, Trial Afforestation Research Station, Kaduna, Nigeria

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_18

The Afaka Forest Reserve is located within the transition belt, between the far south and the savanna woodlands in northern Nigeria, where there is a large band of derived savanna, which has undergone modifications due to large-scale anthropogenic activities. Further north of Afaka Reserve, the conditions get drier, with the woody vegetation getting sparser and the trees thornier, typified by mixed deciduous and semi-deciduous woodlands, with characteristic baobabs (*Adansonia digitata*) further north in the Sudan savanna.

The derived savannah and savannah habitats also support large mammals, such as antelopes, elephants, and lions and bush meat from animals such as tree squirrel (*Funisciurus sp.*), pangolin (*Manis tricuspis*), porcupines (*Artherurus africana*), grasscutter (*Thryonomys swinderianus*), giant rat (*Cricetomys gambianus*), monitor lizard (*Varanus niloticus*), antelope (*Tragelaphus scriptus*), and others.

Many important trees and shrub species of economic value found in the savanna woodlands and montane forests include neem (*Azadirachta indica*), shea butter (*Vitellaria paradoxum*), silk cotton tree (*Ceiba pentandra*), locust bean (*Parkia biglobosa*), acacia (*Acacia nilotica*), date palm (*Phoenix reclinata*), tamarind (*Tamarindus indica*), and moringa (*Moringa oleifera*). The plants of medicinal and culinary values include bitter leaf *(Vernonia amygdalina*), ginger (*Zingiber officinale*), bitter kola (*Garcinia kola*), and *Tetrapleura tetraptera.*

About 150 types of NTFPs are of high economic value in international trade (Bolaji-Olutunji and Osadebe 2010). An estimated eighty per cent of the population of developing world rely on NTFPs as their primary source of income, food, nutrition, and medicine. Whereas the uses of NTFPs may vary from one place to another because of the heterogeneity of the community traditions and beliefs in many countries, they are generally recognized to play an important role in the economy of local communities around forests (Maske et al. 2011). Forests are known repository for cultural, household, and industrial products such as nuts, fruits, mushrooms, honey, insects, snails, bush meat, organic fertilizers, raw materials for construction, fodder, medicinal extracts, cosmetic products, natural dyes, tannins, fibre, gums, resins, latex, essential oils, spices, decorative articles, edible oils, pelts, bones, horns, plumes, hides and skins, phyto-chemicals, non-wood ligno-cellulosic products, and aromatic chemicals.

The expansion of NTFP exploitation *vis-a-vis* timber forest product (TFP) extraction provides a strong basis for sustainable biodiversity of the forests (Belcher et al. 2003; Lindenmayer et al. 2006), environmental protection and climate change mitigation and adaptation (Nadkarni and Kuel 2013), conservation of culture and spiritual traditions (Roland and Oyelana 2014), and bio-energy/biofuel (Yahaya 2015; Nadkarni and Kuehl 2013).

The context of environmental-social protection derives from the important role forests play especially as social safety-nets for poor and vulnerable (agricultural) communities in times of economic or agricultural stress. Forest products provide food and nutrition substitutes; examples are wild fruits, leafy vegetables, bush meat, fresh and dried nuts, wild honey, wild mushroom, medicinal products, etc. In other word, the various social and economic services forests are known to perform, especially in emergency situations for food and nutrition, confer on it a veritable instrument of pseudo-social protection strategy. Therefore, the correlation between environmental life support of forests and poverty is a strong type, such that the social and economic balance of the society would be altered by such activity as deforestation that threatens the carrying capacity of forests (Kushwaha et al. 1999).

In broad sense, social protection involves supporting those who are poor and vulnerable, like women, children, elderly, people living with disabilities, displaced persons, unemployed, etc. The debate about which interventions constitute social protection and which category they fit under is apt, as social protection overlaps with a number of livelihoods, human capital, and food security interventions (Harvey et al. 2007).

Social protection intervention is contemplated in the face of acute poverty and inequality in households. Nigeria is sufficiently in need of social protection intervention in many different social considerations. For instance, Nigeria was ranked by Oxfam Group as a country with the world highest inequality in 2017 for a second consecutive time, which was attributable to low social spending on health, education, and social protection.

Gini index (a measure of inequality) for Nigeria was reported to be 42.95 in 2010 (World Bank 2010), which compared with 0.356 for 2004 and 0.41 in 2013, and 0.391 in 2016 (NBS 2018). Most developed European nations tend to have Gini coefficients between 0.24 and 0.36 while United States' Gini coefficient is above 0.4, indicating that United States has greater inequality than EU nations (Wikipedia 2019). Using the Gini index can help quantify differences in welfare and compensation policies.

Based on the context of income inequality and poverty, Nigeria and Brazil shared similar historical socio-economic antecedents. Brazil and Nigeria had one of the highest rates of inequality in the world, and poverty rates were high, over 20% of the population lived below national poverty lines, and 7% or more were extremely poor. In Brazil, however, within two decades, levels of inequality and poverty declined, and the Gini index also fallen significantly by 5.2 points, from 59.4 to 54.2, and the percentage of households living below the poverty line halved between the early 1990s and 2008, falling from 36.0% to 17.2%. The success story of Brazil in the steady declining poverty and inequality lies in its successful implementation of social protection instruments (Barbosa and Oliviera 2013). Nigeria, on the other hand, started making considerable efforts to address the structural causes of poverty and inequality only in the past decade. However, unlike Brazil, governments in Nigeria lacked the political will to implement important policies, such as real-time increases to the minimum wage; a commitment to reducing child labour and regulating the labour market; provision of subsidized credit for agriculture; and improving the efficiency of public services and increasing federal expenditure on social policies such as social work, health care, education, employment and income, land development, housing, food, and nutrition (Beghin 2008).

Poverty of marginalized groups like people living in proximity to forests can be worsened, in such a way that, while people living around forests areas largely depend on the natural resources found in forest environment, such as collection of non-timber forest products (NTFPs) to serve as sources of income, food, nutrition, energy security, etc.; however, in an attempt to solve the problem of poverty by relying on NTFPs, such short-term poverty trade-off can generate long-run environmental problem such as biodiversity loss if NTFP extraction and collection are not properly managed.

The ‘protection’ in this context—whether of the natural forest environment or social welfare—refers to the double coincidence of interventions to support the capacity of forests to provide sustainable ecological services to society, as well as providing intervention to reduce poverty. The primary objective of this chapter, therefore, is to analyse NTFP income in relation to income from non-NTFPs, to assess the degree of income inequality and poverty among the two groups, for an informed policy on social protection strategy in the communities.

2 Conceptual Framework

2.1 Social Environmental Protection

There are different conceptual approaches to analysing social protection objectives and impacts, namely transformation, human capital, vulnerability, and human rights (Browne 2015). Devereux and Sabates-Wheeler (2004) provide the most commonly used conceptual framework which describes four social protection functions (PPP + T framework), namely protective, preventative, promotive, and transformative.

The first three functions in the PPP + T framework were originally conceptualized by the International Labour Organization (Browne 2015). The addition of the transformative element positions social protection not just to alleviate poverty but to transform lives through pursuing policies that rebalance the unequal power relations which cause vulnerabilities. The dimension of environmental protection conceptualizes a social protection framework in terms of supply and demand (Fig. 1). The demand side comprises the needs by the poor and vulnerable people for support, and supply side involves the provision of NTFPs and environmental services. The demand may be ‘protective’, meaning shielding the poor from extreme poverty by providing reliefs in form of food and income from NTFPs; or ‘preventative’, referring to reliance on NTFPs and other sources of sustenance to avert deprivation or extreme poverty; ‘promotive’, providing a better copping mechanism for the poor that depend on NTFPs through capacity building and income; and ‘transformative’, increasing social equity and inclusion of NTFP collectors and recognizing their rights to quality life. The social protection domain represents society where non-poor, poor, and vulnerable live and from where they exert demand on the forest in the natural environment.

Social protection exists in different forms, such as safety-nets or helping people meet immediate basic needs in times of crisis. Moreover, NTFP is able to justify this definition by offering poor and the marginalized people access immediate mitigative response to shocks and to smooth consumption. Most social protection frameworks also conceptualize social protection as an investment in human capital which builds

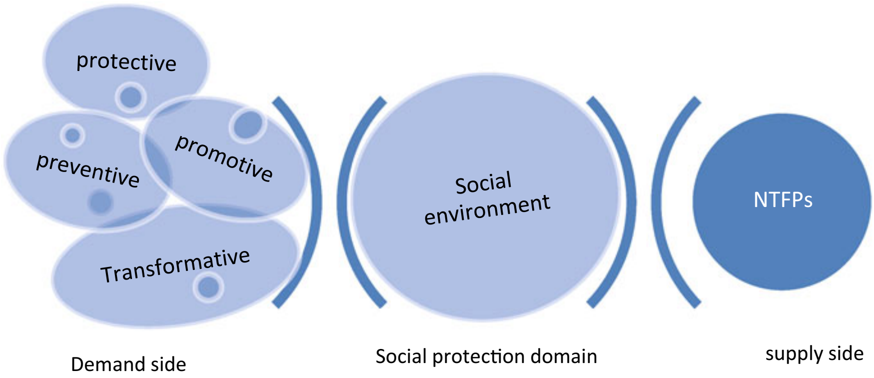


Fig. 1 Social and environmental protection framework

the capacities and the accumulation of productive assets (Barrientos 2010), thereby breaking the intergenerational transmission of poverty. Social and environmental protection, therefore, can contribute to human capital directly, by providing access to NTFPs such as food, environmental services, and opportunity for skill acquisition, or indirectly, through income generated from NTFP sales.

2.2 Non-timber Forest Products

Non-timber forest products (NTFPs), as an ecological concept, may be defined as all biological materials, other than timber, which are extracted from forest for human use (NTFP-EP 2019). FAO (2010) classified NTFPs into plant and animal products/raw materials on the basis of sources and uses. The plant products/raw materials, among other things, include food, fodder, for colourants and dyes, material for medicine, and aromatic products. Similarly, the animal products/raw materials include living animals, hides and skins, wild honey and beeswax, and bush meat, among other things. According to Mathur and Shiva (1996), “all products obtained from plants of forest origin and host plant species yielding products in association with insects and animals or their parts and items of mineral origin except timber, may be defined as ‘Non-Wood Forest Products’ (or ‘Non-Timber Forest Products’)”. According to Beer and McDermott (1989), NTFPs are derived from two main sources, namely the natural forest, human influenced systems such as plantations, and modified forests.

In many developing countries, economic welfare has historically been influenced by natural resources such as forests (Fletcher et al. 1991). On this basis, the role of any natural resource in the economic welfare of rural economies should be evaluated in three dimensions (Kant and Nautiyal 1996): (1) its economic contribution to the local economy; (2) its implications for equal income distribution (or low levels of inequalities); and (3) the seasonal spread of its contributions. Specifically, the returns from NTFPs in tropical forests for some local communities are of comparable magnitude to those from other sources of income such as agriculture. This is so because returns from NTFPs enhance the income of poor people proportionally more than that of other livelihood systems, thus reducing inequalities. Further, the availability of these returns throughout most of the year also provides security or safety-nets to vulnerable people by shielding them from the effects of the wide fluctuations in agricultural income. Equally important is the 'open access' or near open access nature of forests has implication for low equalizing income.

2.3 Poverty and Inequality

Inequality is related to poverty. It is the relative distribution of resources or well-being within the economy which gives a picture of equity or otherwise. Inequality focuses on the relative distribution of wealth, such as income or consumption, across the whole population. But poverty and inequality are not the same. However, the existence of poverty portrays inequality in the distribution of well-being. Inequality re-enforces poverty, and either of these can change without affecting the other (Haughton and Khandker 2009).

According to the United Nations Research Institute for Social Development (UNRISD) (2010), poverty and inequality must be considered as interconnected parts of the same problem, given that high levels of inequality make it harder to reduce poverty even when economies are growing. Evidences from global economic outlook have revealed that inequality is generally more predominant in poor countries than in rich ones. Consequently, poverty is closely related to various dimensions of inequality, including income status, gender, ethnicity, and location.

This explains why such countries have witnessed economic growth over the last decades without an accompanying improvement in the welfare of their people. For instance, it is estimated that there are 1.2 billion extremely poor people and sub-Saharan Africa has the top ten countries in the world with the unacceptably high poverty incidence (World Bank 2016), and Nigeria ranks second to India among the top countries globally with the highest population of the poor (World Bank 2016). Nigeria is ranked 158 on the Human Development Index (UNDP 2019). This represents a paradox of development (attributable to income inequality) when viewed against the background of the economic growth witnessed for about a decade within the same period (UN 2015; NBS 2012).

2.4 Measurement of Inequality

One common way of measuring income inequality is to rank all households by income, from lowest to highest, and then to divide all households into five groups with equal numbers of people, known as quintiles. This calculation allows for measuring the distribution of income among the five groups compared to the total. The first quintile is the lowest fifth or 20%, the second quintile is the next lowest, and so on, with the fifth quintile being the highest. In this approach, income inequality can be measured by comparing what share of the total income is earned by each quintile.

The other method and perhaps the most popular measurement tool for inequality is the Gini index. In particular, the Gini coefficient technique is often used, because Gini results are easily interpretable with the aid of a Lorenz Curve, the Gini technique allows easy decomposition of inequality by income sources, and the technique lends itself to easy-to-interpret decompositions of income effects (Lopez-Feldman et al. 2007). With the technique propounded by Lerman and Yitzhaki (1986), inequality can be decomposed into two parts: inequality between groups (or horizontal inequality) and inequality within groups (or vertical inequality).

3 Methodology

3.1 Study Area

Afaka Forest Reserve was established as an experimental plantation with the primary aim to curtail the imminent loss of the semi-arid environment of the Northern Guinea Savannah of Nigeria to desertification. The Reserve occupies an area of about 7093.12 ha of land and lies between latitudes 10°35′10″ N and 10°37′48″ N and longitudes 7°18′49″ E and 7°21′58″ +E of the Greenwich meridian (Otiwa 2015; Yahaya 2015; JICA 1991).

3.2 Data Collection

The study was conducted to assess the livelihood systems, poverty, and income equality among communities living around the Reserve. The data were collected between December 2016 and March 2017. Data for this study were collected from Udawa, Buruku, and Kuriga communities in Chikun Local Government Area (LGA) and Rigasa, Mando (Sabon-Afaka), Likora, Gwazaye, and Hayin Dan-mani communities in Igabi LGA. The eight communities were purposively selected based on their proximity to the Reserve. A total of 204 households were systematically and proportionately selected for the study, viz. Rigasa (60), Mando (50), Gwazaye (25), Likora (10), and Hayin Dan-mani (10), all in Igabi LGA, while the samples from Chikun LGA were Buruku (25), Udawa (25), and Kuriga (10). The major economic activities of the communities include, among others, farming, livestock rearing, hunting, wild fruit collection, weaving, and trading.

3.3 Data Analysis

The data were analysed for Gini coefficients to estimate the effects of NTFP incomes on income inequality as an index of forest safety-net, and Foster-Greer-Thorbecke (FGT) was used to measure the effect of NTFP income on poverty profile. The Gini coefficient is a common measure of income inequality across individuals or households (Fisher 2004; FAO 2006; Lambert 1993).

The Gini coefficient was used to measure the impact of NTFP income on inequality in the study area. Therefore, to estimate the effect of NTFP income on inequality, the Gini coefficient model proposed by Lerman and Yitzhaki (1986), adopted by Fonta and Ayuk (2013), was used. Assuming k is any income source [and in this study incomes came from: NTFPs (x_1), agriculture (x_2), artisanal activities (x_3), trading (x_4), paid employment (x_5), and gifts (x_6)], the Gini coefficient for any particular income source k was computed as:

$$G_T = 2\frac{\text{COV}\ [Y_K, F(Y_K)]}{\mu_k} G_K = 2\frac{\text{COV}\ [Y_K, F(Y_K)]}{\mu_k} \tag{1}$$

where Y_K = pooled income of the household (i.e. NTFPs and other income sources); $F(Y_K)$ = the cumulative distribution of income source k; μ_K = mean household income; and G_K = the Gini coefficient of each income source k. Similarly, assuming G_T as the Gini coefficient of total income, then the Gini coefficient (G_T) of total household income is given by:

$$G_T = 2\sum_{k=1}^{k} \text{COV}[Y_k, F(Y_k, F(Y_k)/\mu_\tau)] \tag{2}$$

This also equates:

$$G_T = \sum_{k=1}^{k} S_k G_k R_k G_T = \sum_{k=1}^{k} S_k G_k R_k \tag{3}$$

where S_k represents the share of household income k on total income, and G_k measures the Gini coefficient of each income source k, while R_k measures the Gini correlation between income source k and the distribution of total income.

Hence, Eq. (1) enables the decomposition of the influence of any income component such as NTFP income on total income inequality to be determined, thereby answering the following three questions:

(i) What is the contribution of the income k to total income (S_k)?
(ii) How equally (or unequally) distributed is the income k relative to G_k? and
(iii) What is the correlation between the income sources and the distribution of total income (R_k)?

The effect of a small change from any income source k (holding others constant) is therefore given by:

$$\frac{\delta G_T}{\delta k}/G_T = (S_k G_k R_k)/G_T - S_k \tag{4}$$

4 Results and Discussion

The non-timber forest products extracted from Afaka Forest were categorized into six major groups, namely food, medicine, fuel, construction, animal feed, and other raw material. Figure 2 provides example of the NTFPs hunted or collected and the percentage utilization of each product as household food for Afaka Forest communities. Although no attempt has been made to establish any relation between consumption and income in this study, the result showed a relatively high dependence on NTFPs for food, especially meat supply, such as hedgehog, squirrel, grasscutters, rabbits, and porcupine. The over 80% of the households depending on NTFP meat supply was an indication of extreme poverty in the communities. Moreover, edible insects such as grasshoppers (or locusts) and termites and fish like tilapia added to the source of protein for the households. Very often, poor households spend less on proteins because of the constrained food budget since proteins tend to be relatively expensive. The fact that forests tend to be home to very poor community because of the proximity to sources of food and nutrition in form of fruits, nuts, mushrooms, snails, wild honey, bush meat, fodder, etc., is an indication of high poverty level in these communities.

Figure 3 result revealed the concentration of households on individual NTFPs in terms of collection. Firewood, wild fruit, and vegetable collection exceeded 70% mark, which was considered very high. Firewood collection has been identified as one of the most serious environmental concerns of many poor countries, especially in rural communities south of the Sahara where Nigeria has the largest population. However, under a well-controlled NTFP extraction, firewood collection without felling of trees can act as a modifier of forests by selective felling and topping of trees. However, firewood collection and sales, which have become a big business in most parts of Nigeria, especially in the north of the country, are derived from cutting down of a whole tree without replacement. This practice is considered to be contributory to the fast encroachment of Sahara desert and increasing evidences of climate change in northern part of the country. These factors which include erratic rainfall pattern—its arrival, cessation, and volume as well as other elements of weather like temperature, relative humidity, wind, etc., and environmental factors such as flooding, drought, and erosion have exacerbated in recent years, especially in northern Nigeria.

The study showed that nearly all the households participated in firewood collection in the communities Fig. 4. Firewood utilization primarily constituted energy demand of households, both as fuel wood and for charcoal production. Wild fruit

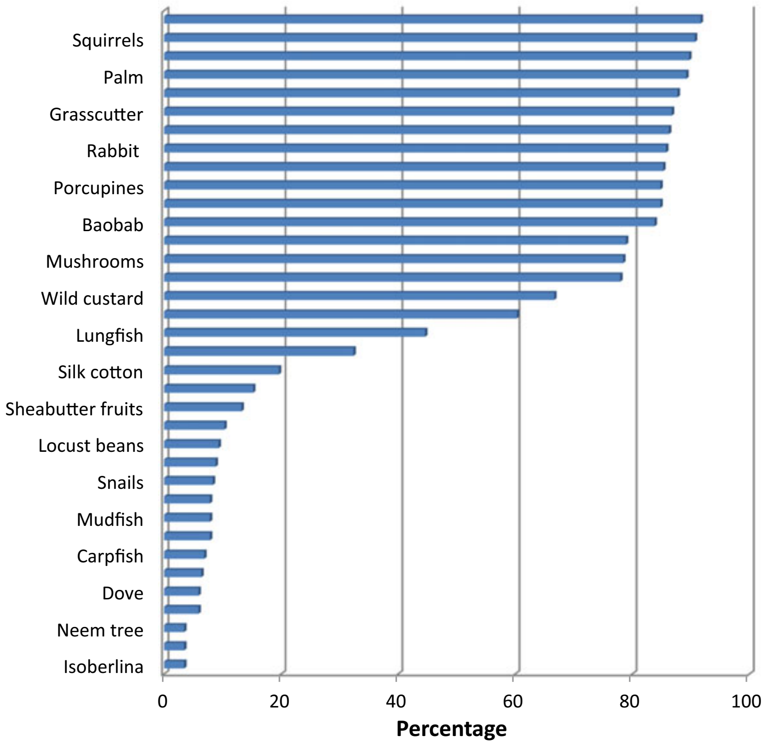


Fig. 2 Percentage utilization of NTFPs as household food

and vegetable collection had taken second and third positions, respectively, among the households. This further indicated the poor income status of households in the communities, having to rely on forest products for sustenance, as well as stressing the importance of forests as repository for safety-nets. Some of the NTFP extractions were carried out by relatively fewer households, namely porcupines and resins. Porcupines are a delicacy in many African dishes because of the succulent and sweet taste of the meat. The relatively few households that supplied porcupines, perhaps through hunting or poaching at the Reserve, may be due to the declining population of African porcupines, which has implication for the porcupine extinction. Plant resins, on the other hand, are valuable for production of varnishes, adhesives, and food glazing agent, among other uses, and were mostly collected for sale in the local market than direct utilization by households.

Figure 5 also shows the ten topmost NTFPs on the basis of their estimated gross incomes realized. Firewood accounted for the highest gross income of N4, 661,400, followed by electric poles with estimated gross income of N2, 698,800. Similar finding by Inoni (2009) showed that income from forest resources exploitation contributed 41.3–67.2% of total household's income, the proportion being greater for poorer families than high-income groups. On the one hand, the high incomes

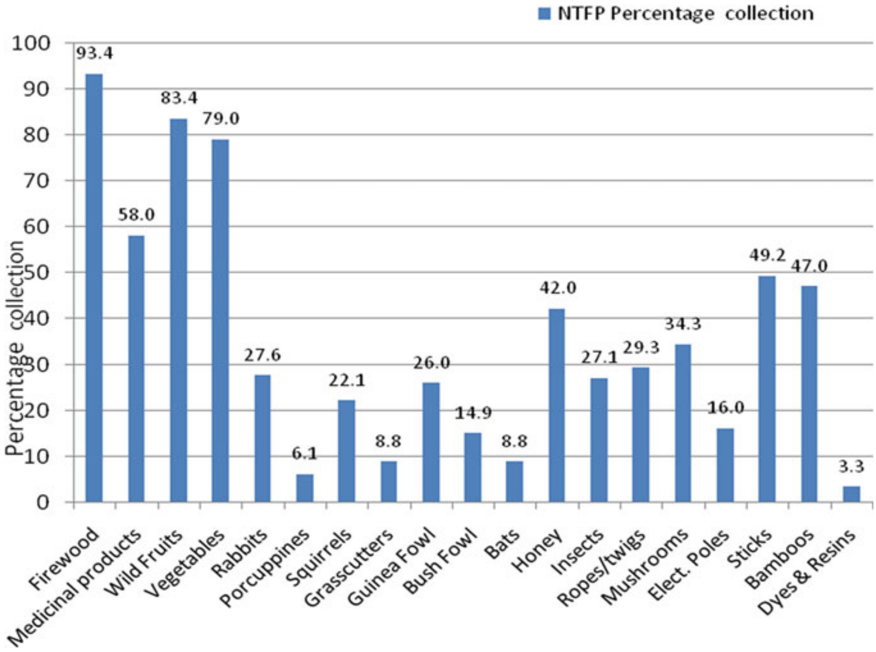


Fig. 3 NTFP percentage utilization for food in Afaka Forest Reserve

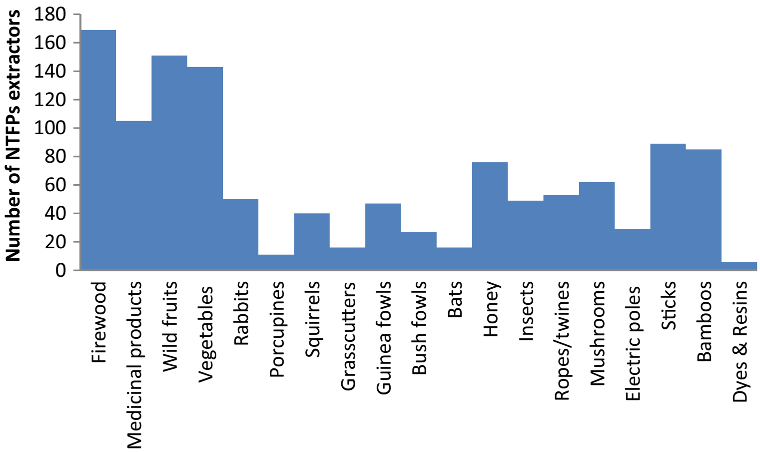


Fig. 4 NTFP collection from Afaka Forest

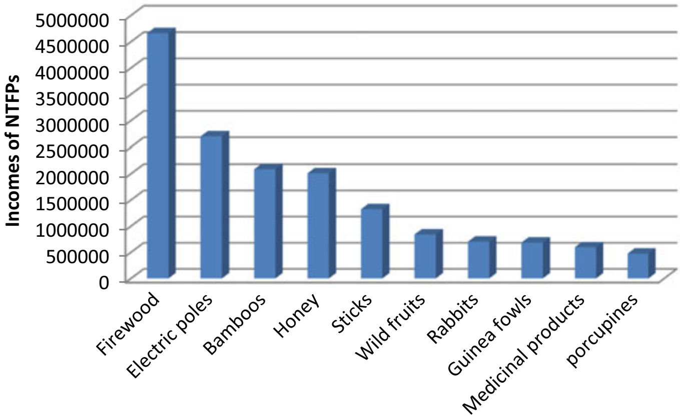


Fig. 5 Incomes from ten topmost NTFPs in Afaka Forest

derived from firewood and electric pole extractions have implication for high rate of exploitation of the forest, which would predispose the forest to tree species loss and/or extinction and reduced carbon sequestration. Casella et al. (2020) noted that the surface area of forests degraded by forest exploitation represents between 12,000 and 20,000 km^2 per year between 1999 and 2002.

In both cases of exploitation of the forest trees for electric poles, firewood extraction and changes in the ecological services in Afaka Forest Reserve, the case of long-term social cost to society and short-term private benefits could be considered, 'as all the cost and benefit streams of the actions, regardless to whom in society they accrued, constituted an abrasion to the concept safety-nets'.

The negative external effects of private production/consumption decisions on sustainability forests and NTFPs in Afaka Forest Reserve have implication for an effective and comprehensive policy on afforestation and reforestation programmes of government. Consequently, the onus rests on the state to bridge poverty gaps (including money, food, and material poverty) through effective social protection instruments such as cash transfers (conditional and/or unconditional), subsidies, and food voucher (Holmes et al. 2011). Social protection is theoretically conceived as part of the 'state-citizen' contract, in which states and citizens have rights and responsibilities to each other (Harvey et al. 2007).

The trade-off between public loses and private benefits or social externality is a common phenomenon in Nigeria, where there is high level abuse of public goods such as forests (Ochi 2002). There is much reliance of the poor on forests for supply of food, medicaments, fuel wood, construction materials, etc., and forests should be allowed to serve its traditional function as safety-nets or wealth of society.

Figure 6 shows the per capita income among Afaka communities' households, which has been categorized into two, namely per capita income of households living only on NTFPs (PMIHH1) and per capita income of households with NFTP income as a supplement (PMIHH2). The PMIHH2 was much higher than PMIHH1. The difference was highly significant ($P < 0.001$). This finding brings to the fore the existence of income inequality among rural households not only among urban households. The nature of forest as a public good makes it accessible to the general public for exploitation, and the core poor, moderately poor, and non-poor use NTFP income to stretch the household budget. Consequently, forests often come under severe pressure due to competition from different social and economic classes. However, such open access tends to negate the importance of forests as natural safety-nets for the core poor group. Notwithstanding, it also stresses the role forests play as pseudo-social protection instrument by augmenting the incomes of households, comparable to the conventional social assistance. Social transfers may offer a tremendous relief to core poor households living in proximity to forests and could be a relevant strategy to bridging income inequality gap by raising per capita income of households. Social transfers come in different variants, namely cash transfer, inputs transfer, food transfer, work-for-food, etc. (Holmes et al., 2011; Hailu 2009; Fletcher 1991). While classic economic theory suggested that inequality is a natural by-product of rapid growth, recent research has shown that high levels of inequality and poverty can undermine economic growth through several channels, including weak social cohesion, fiscal instability, biased social spending, elite domination, insecurity, etc. (Birdsall 2007; Santos 2010).

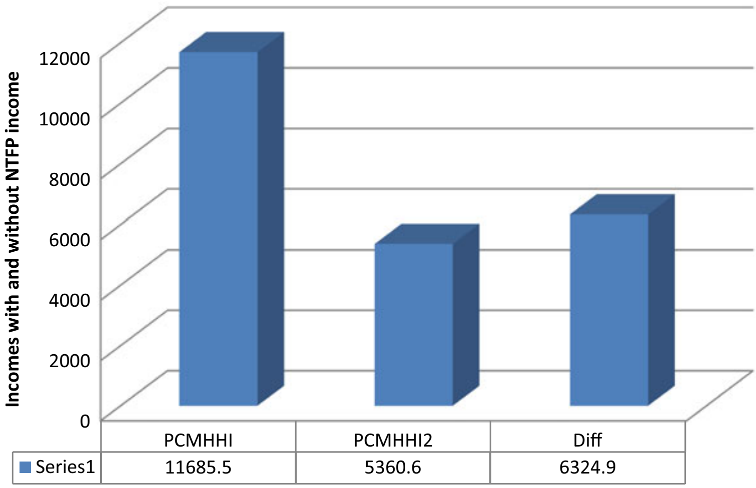


Fig. 6 NTFPs-based per capita incomes in Afaka communities

4.1 Decomposition of Gini Index by Income Sources

Decomposition of income inequality provides some idea on the concentration of total inequality. In other words, the decomposition shows how each component of total incomes stands in terms of contribution to the total inequality (Araar 2006; Lorenzo and Libertati 2006). Gini index measures the extent to which the distribution of income among individual households within communities deviates from a perfectly equal distribution.

There were six major sources of income in this study investigated in terms of share of total income and contribution to income inequality, namely NTFPs, crop farming, crafts, trading, paid employment, and pension (Table 1). The study found Gini coefficient of 0.3427 for the total income inequality. The decomposition of the Gini coefficient shows that the average monthly farm income ($AMFAR_{INC}$) accounted for the highest share (0.5975 or 59%) but had a Gini coefficient of 0.4028 while the least share of income (0.0073 or 0.7%) came from trading ($AMTRAD_{INC}$). Income from NTFPs ($AMNTFP_{INC}$) accounted for 8% share of total income with a Gini coefficient of 0.4426, and its relative contribution to income inequality was 0.0178, implying that NTFP incomes had a reducing power on inequality, suggesting that a 10% rise in NTFP income would result in 0.178% increase in total income inequality (or relative poverty index), which compares with the 59% coming from farming income. Fisher (2004) obtained a similar result when he reported that NTFP income reduced income inequality by 12%. The reported income from NTFP compared with $AMFAR_{INC}$, and $AMPE_{INC}$, which accounted for the majority in this study, has implication for social protection in terms of social transfers. However, when viewed from the context of complementary income, NTFPs play important role in strengthening household income budgets.

4.2 Decomposition of NTFP Income Gini Index by Selected Socio-economic Characteristics

The further analysis showed the distribution of NTFP incomes among different categories of the population. Hence, the income distribution was examined in the contexts of gender, education, and primary occupation of the household heads. Table 2 shows that female-headed households had a relatively higher Gini coefficient of 0.4711 than their male counterparts, implying that female-headed households in the study area had higher propensity to poverty. On the whole, the relative contribution to inequality accounted for within and between male and female groups was 81% and 14%, respectively. Gender is a key dimension in income inequality, and women tend to be disadvantaged relative to men in most spheres of lives (UNRISD 2010). The maleness of Nigerian society, in general, and the study area, in particular, tends to support the gender hypothesis occasioned by a combination of traditional factors, such as limited access to land, religious practices, such as women seclusion in Muslim

Table 1 Decomposition of inequality by sources of income among the households

Sources	Income share (S_K)	Gini correlation (R_K)	Gini index (G_k)	Absolute contribution ($S\_k * R\_k * G\_k$)	Relative contribution ($S\_k * R\_k * G\_k/G$)
1. $AMNTFP_{INC}$	0.0842	0.1635	0.4426	0.0061	0.0178
2. $AMFAR_{INC}$	0.5975	0.7229	0.4028	0.1740	0.5078
3. $AMCRAF_{INC}$	0.0450	0.2577	0.8808	0.0102	0.0298
4. $AMTRAD_{INC}$	0.0073	−0.3844	0.8281	−0.0023	-0.0068
5. $AMPE_{INC}$	0.2390	0.7753	0.8062	0.1494	0.4360
6. $AMPEN_{INC}$	0.0270	0.2051	0.9541	0.0053	0.0154
Total	1.0000	–	–	0.3427	1.0000

Note $AMNTFP_{INC}$ average monthly non-timber forest income; $AVMFAR_{INC}$ average monthly farm income; $AMCRAF_{INC}$ average monthly craft income; $AMTRAD_{INC}$ average monthly trade income; $AMPE_{INC}$ average monthly paid employment income; $AMPEN_{INC}$ average monthly pension income

households, etc. Consequently, female gender tends to have limited opportunities and be more vulnerable and predisposed to poverty, disease, and other social and economic challenges than the male counterpart.

The decomposition of income inequality by educational status of the household heads showed that, although the household heads having tertiary education had the lowest Gini coefficient of 0.37, their share of NTFP incomes was 9% (Table 3). The highest income share came from non-formal education (37%), also with the second highest Gini coefficient (0.47), which may be attributed to the relatively fewer people involved, but generated high income from the types of NTFPs such as electric poles. The lowest Gini coefficient for tertiary education was supported by education hypothesis, which posits there is an inverse relationship between education

Table 2 Decomposition of NTFP income by gender of household head

Group	Gini index	Population share	Income share	Absolute contribution	Relative contribution
Male-headed HH	0.4017	0.8847	0.9425	0.3350	0.7978
Female-headed HH	0.4711	0.1153	0.0575	0.0031	0.0074
Within	–	–	–	0.3381	0.8052
Between	–	–	–	0.0578	0.1376
Overlap	–	–	–	0.0240	0.0572
Population (total)	0.4199	1.0000	1.0000	0.4199	1.0000

HH Household head

Table 3 Decomposition of NTFP income by educational status of household head

Group	Gini index	Population share	Income share	Absolute contribution	Relative contribution
Non-formal edu	0.4741	0.3334	0.36673	0.0386	0.0919
Primary edu	0.4245	0.2038	0.2339	0.0202	0.0482
Secondary edu	0.4826	0.3104	0.3083	0.0462	0.1100
Tertiary edu	0.3747	0.1525	0.0905	0.0052	0.0123
Within	–	–	–	0.1102	0.2624
Between	–	–	–	0.0891	0.2122
Overlap	–	–	–	0.2206	0.5254
Population (total)	0.4199	1.0000	1.0000	0.4199	1.0000

and poverty, suggesting that the attainment of tertiary education would bring about income inequality reduction. Moreover, the relative contribution to income inequality by tertiary education is the lowest, which implied that a difference in income among tertiary income earners is not clear-cut.

The analysis of income inequality by occupation depicted paid employment as having the highest Gini coefficient (0.49) with 17% NTFP income share (Table 4). In other word, paid employment has higher tendency to create income inequality, which may be attributed to the wide labour wage differentials for different levels of education, namely primary, secondary, and tertiary. Conversely, hunting has the lowest propensity for income inequality among hunters due to the close similarity between hunters in terms of income. The result further showed that the most important category of the occupation is farming with NTFP income share accounting for 64% as well as accounting for the largest share of the population (57%), consequently, the large relative contribution to the total income, which has implication for improved methods of farming. In other word, an improvement in the income and its distribution among farmers who also collected NTFPs would improve the welfare of the communities around the Reserve.

5 Conclusion

About 803 thousand people who live in proximity to Afaka Forest Reserve depend on the forest for their subsistence and income. Most of this population were wholly or partially dependent on the forest for food, especially meat supply, such as hedgehog, squirrel, grasscutters, rabbits, porcupine, etc. Edible insects such as grasshoppers (or locusts) and termites and fish like tilapia provided the source of protein for households. The over 80% households depending on NTFP meat supply were an indication

Table 4 Decomposition of NTFP Gini index by occupation of household head

Group	Gini index	Population share	Income share	Absolute contribution	Relative contribution
Farming	0.3966	0.5699	0.6428	0.1453	0.3460
Hunting	0.1969	0.0224	0.0308	0.0001	0.0003
Trading	0.4882	0.0934	0.0782	0.0036	0.0085
paid employment	0.4889	0.2120	0.1713	0.0178	0.0423
Others	0.3712	0.1022	0.0769	0.0016	0.0039
Within	–	–	–	0.1684	0.4010
Between	–	–	–	0.0872	0.2076
Overlap	–	–	–	0.1643	0.3913
Population (total)	0.4199	1.0000	1.0000	0.4199	1.0000

of extreme poverty among majority households in the communities. In terms of the concentration of households on individual NTFP collection, firewood, wild fruit, and vegetable collection exceeded 70% mark. Firewood was collected by nearly all the households in the communities, which has strong implication for forest over-exploitation and environmental degradation. Primarily, firewood utilization included energy for households, both as fuel wood as well as for charcoal production. Wild fruits and vegetables served as food nourishment and for production of varnishes, adhesives, and food glazing agent, among other uses. Firewood collection accounted for the highest gross income of N4, 661,400, followed by electric poles N2, 698,800.

The high incomes from firewood collection and electric pole production would impact negatively on the sustainability of forests due to concomitant high rate of exploitation of the forest, which may predispose the forest to tree species loss and/or extinction and reduced carbon sequestration. This would also have implication for trading-off public ecological goods and services for private short-term benefits. Moreover, forests act as good sink surfaces for carbon dioxide and other dangerous greenhouse gases from exposing the atmosphere to direct effects of anthropogenic activities on the ozone layer, which acts as an effective screen from dangerous greenhouse gases, thereby protecting earth surface from global warming.

The negative external effects of private production and consumption decisions on ecological resources are the bane of governance in Nigeria, where majority of the population are left to scavenge for short-run survival decisions, irrespective of the long-run negative externalities. Consequently, it becomes the responsibility of the state to bridge poverty gaps (including money, food, and material poverty) through social protection instruments such as cash transfers. There is much reliance of the poor on forests for food, medicaments, fuelwood, construction, raw materials, etc., rather than allowing forests to serve as safety-nets or net wealth of society. In order to secure and improve the socio-economic well-being of the poor in Nigeria, donor agencies have embarked on development of livelihood strategies, such as building earth dams and production of *Jatropha curcas* in rural communities (Saminu et al. 2010).

The per capita income among Afaka communities' households has been categorized into two, namely per capita income of households living only on NTFPs (PMIHH1) and per capita income of households with NFTP income as a supplement (PMIHH2). The result showed PMIHH2 was much higher than PMIHH1. The difference was highly significant ($P < 0.001$). This finding brings to the fore the existence of income inequality not only among urban households, but also among rural households living in proximity to forests. The nature of forest as a public good makes it accessible to the general public for exploitation—the core poor, moderately poor, and non-poor groups use NTFP income to stretch the household budget. Consequently, forests often come under severe pressure due to competition from different social and economic classes. However, such open access tends to negate the importance of forests as natural safety-nets, for the core poor group on one hand and the general public on the other. Notwithstanding, the natural satety-nets also stress the role forests play as pseudo-social protection instrument.

The decomposition of income inequality provides some idea on the concentration of total inequality. Six major sources of income were investigated in terms of share of total income and contribution to income inequality. These include NTFPs, crop farming, crafts, trading, paid employment, and pension. The total income inequality for the study was 0.3427 Gini coefficient. The decomposition of the Gini coefficient showed that the $AMFAR_{INC}$ accounted for 59%, with a Gini coefficient of 0.4028, while $AMTRAD_{INC}$ accounted for 0.7% of the income. The $AMNTFP_{INC}$ accounted for 8% share of total income with a Gini coefficient of 0.4426 and the relative contribution to income inequality of 0.0178, implying that NTFP incomes had a reducing power on inequality. Furthermore, the income distribution was examined in the contexts of gender, education, and primary occupation of the household heads. The female-headed households had a relatively higher Gini coefficient of 0.4711 than their male counterparts, which suggested that female-headed households in the study area had higher propensity to be poor. On the whole, the relative contribution to inequality accounted for within and between male and female groups was 81% and 14%, respectively. The maleness of Nigerian society, in general, and the study area, in particular, tended to support gender hypothesis occasioned by a combination of traditional factors, such as limited access to land, religious practices, such as women seclusion in Muslim households, etc. Consequently, female gender tends to have limited opportunities and be vulnerable and predisposed to poverty, disease, and other social and economic challenges compared to the male counterpart.

The decomposition of income inequality on the basis of educational status of the household heads showed that, although the household heads having tertiary education had the lowest Gini coefficient of 0.37, their share of NTFP incomes was 9%. The highest income share came from non-formal education (37%), which also had the second highest Gini coefficient (0.47), and generated the highest income from NTFPs largely sale of electric poles. The lowest Gini coefficient for tertiary education was supported by education hypothesis, which posits an inverse relationship with poverty. Moreover, the relative contribution to income inequality by tertiary education was the lowest, which suggested that differences in income among tertiary income earners cannot easily be explained in relation to the income inequality.

The analysis of income inequality based on occupation depicted paid employment as having the highest Gini coefficient (0.49) with 17% NTFP income share. In other word, paid employment has higher tendency to create income inequality, which may be attributed to the wide labour wage differentials among the different levels of education, namely primary, secondary, and tertiary; even among tertiary education, there are differences in income attribution. Conversely, hunting had the lowest propensity for income inequality among hunters due to the close similarity of the income among hunters. The result further showed that the most important category of the occupation was farming, with NTFP income share accounting for 64% as well as accounting for the largest share of the population (57%). Consequently, the large relative contribution to total income has implication for improved methods of farming. In other word, an improvement in the income and its distribution among farmers (who also collected NTFPs) would improve the welfare of the communities around the Reserve.

References

Araar A (2006) On the decomposition of the Gini coefficient: an exact approach, with an illustration using Cameroonian data. CIRPEE (Centre interuniversitaire sur le risqué, les politiques economiques et l'emploi). Universte laval, Sainte-Foy, Quebec, Canada, Working Paper 06-02

Barbosa TV, Oliviera MJ (2013) Brazil social policy in the 21st century: governance, partnership and participation

Barrientos A (2010) Social protection and poverty, social policy and development programmes paper No. 42, United Nations Research Institute

Beer JH, McDermott M (1989) The economic value of non-timber forest products in South East Asia. Netherlands Committee for IUCN, Amsterdam

Beghin N (2008) Notes on inequality and poverty in Brazil: current situation and challenges. Oxfam, Oxford

Belcher B, Ruiz-Perez M, Achdiawan R (2003) Non-timber forest products (NTFPs), small-scale logging and rural livelihoods. In: Paper presented at the international conference on rural livelihoods, forests and biodiversity 19–23 May 2003, Bonn, Germany, 27p

Birdsall N (2007) The macroeconomic foundations of inclusive middle-class growth: 2020. Focus brief on world's poor and hungry people. Washington DC, IFPRI

Bolaji-Olutunji KA, Osadebe CA (2010) Economic importance of non-timber forest products in Nigeria. In: Popoola L, Iduma FO, Adekunle VAJ, Azeez IO (eds) The global economic crisis and sustainable renewable natural resources management: proceedings of the 33rd annual conference of the forestry association of Nigeria, Benin City Nigeria, 29th Oct 2010, pp 119–122

Browne E (2015) Social protection: topic guide. GSDRC, University of Birmingham, Birmingham, UK

Casella L, Alessi N, Spada F, Agrillo E (2020) Evergreen oak woodlands Southern Europe and Northern Africa, Encyclopaedia of World's Biomes, pp 129–137

de Préneuf F (2013) World Bank: forests and poverty reduction

Devereux S, Sabates-Wheeler R (2004) Transformative social protection, IDS working paper 232. IDS, Brighton

FAO (2006) Inequality analysis: the Gini index. EASYPol, On-line resource materials for policy making, module 040, Food and Agriculture Organization of the United Nations, FAO, 30p

FAO (2010) Global forestry resources assessment, 2010. Food and Agricultural Organization. (FAO). Forestry paper163, Rome, Italy, p 340

Fisher M (2004) Household welfare and forest dependence in Southern Malawi. Environ Dev Econ 9(2):135–154

Fletcher S, White W, Phillips W, Constantino L (1991) An economic analysis of Canadian Prairie Provinces' forest dependent communities. Department of Rural Economy, University of Alberta, Edmonton, p 62

Fonta WM, Ayuk TE (2013) Measuring the role of forest income in mitigating poverty and inequality: evidence from south-eastern Nigeria. Forests Trees Livelihoods 22(2):86–105

Harvey P, Holmes R, Slater R, Matin (2007) Social protection in fragile states. ODI, London. http://www.odi.org.uk/sites/odi.org.uk:files/odi-assetspublications-opinion.files/4547.pdf

Haughton R, Khandker SR (2009) Handbook on poverty and inequality. Published by The World Bank, 1818 H Street NW, Washington, DC 20433, USA

Holmes R, Hagen-Zanker J, Vandemoortele M (2011) Social protection in Brazil: impacts on poverty, inequality and growth. Development Progress, Overseas Development Institute

Igu NI, Nzoiwu CP, Anyaeze EU (2017) Biodiversity and carbon potentials of a Nigerian forest reserve: insight from Niger Basin. J Environ Prot 8(8)

Inoni OE (2009) Effects of forest resources exploitation on the economic well-being of rural households in Delta State, Nigeria. Agricultura Tropica et Subtropica 42(1)

JICA (1991) Management model of industrial afforestation. Japan International Cooperation Agency

Kant S, Nautiyal JC (1996) Forests and economic welfare. J Econ Stud 2(23):31–43

Kushwaha S, Ochi JE, Abubakar MM, Ayoola GB (1999) Effect of chemical fertilizer and animal wastes application on environmental life support using the "Delphi" technique. J Sustain Agric 14(1):91–98

Lambert PJ (1993) The distribution and redistribution of income, 2nd edn. Manchester University Press, Manchester, 307p

Lerman R, Yitzhaki S (1986) Income inequality effects by income sources: a new approach and application to the US. Rev Econ Stat 67(1):151–156

Lindenmayer DB, Franklin JF, Fischer J (2006) General management principles and a checklist of strategies to guide forest biodiversity conservation. In: Biological conservation, vol 131, pp 433–445. www.elsevier.com/locate/biocon. Also available at: www.sciencedirect.com

Lopez-Feldman AMJ, Taylor JE (2007) Does natural resource extraction mitigate poverty and inequality? Evidence from rural Mexco and Lacandona rainforest. Environ Dev Econ 12:251–269

Lorenzo GB, Libertati P (2006) Policy impacts on inequality decomposition of income inequality by income sources, FAO

Maske M, Mungole A, Kamble R, Chaturvedi A, Chaturvedi A (2011) Impact of non-timber forest produces (NTFPs) on rural tribes' economy in Gondia district of Maharashtra, India. Achieves Appl Sci Res 3(30):109–114

Mathur RB, Shiva MP (1996) Standard NTFP classification and documentation manual. Khanna Bandhu, Dehra Dun, pp 1–40

Nadkarni M, Kuel Y (2013) Forests beyond trees: NTFPs as tools for climate change mitigation and adaptation. INBAR working paper no. 74, International Network for Bamboo and Rattan (INBAR), Beijing, China, p 26

NBS (2012) Nigeria poverty profile. National Bureau of Statistics Annual Abstract of Statistics, Abuja

NBS (2018) Snapshot of inequality in Nigeria (2004, 2013 and 2016). National Bureau of Statistics Annual Abstract of Statistics, Abuja

NTFP-EP (2019) Linking people and forests: strategic direction (2016–2019). Non-timber forest products-exchange programme

Ochi JE (2002) Sustainability of environment and agriculture: case of animal wastes and fertilizer application in the Northern Guinea Savannah of Nigeria. FAMAN J 6(1):81–93
Otiwa G (2015) Geographical assessment of Non Timber forest products (NTFPs) in Afaka Forest Reserve, Unpublished M.Sc thesis, Geography Department, Nigerian Defence Academy (NDA), Kaduna
Roland RO, Oyelana AA (2014) Contribution of non-timber forest products to rural household income in Eastern Cape Province, South Africa. Mediterr J Soc Sci 5(23):749–757
Santos L (2010) Bolsa familia programme: economic and social impacts under the perspective of the capabilities. BIEN, Brazil
Saminu IT, Fatimah JE, Ochi, J, Joseph and Abdulkadir (2010) Strengthening adaptation strategies in fragile ecological areas of Bauchi and Jigawa States, Nigeria, Report submitted on Building Nigeria's Response to Climate Change, CIDA.
UN (2015) Transforming our world: the 2030 agenda for sustainable development. Resolution (A/RES/70/1) adopted by the general assembly on 25 Sep 2015, during the seventieth session
UNDP (2019) Human development report: beyond income, beyond average, beyond today: inequality in human development in the 21st century
United Nations Research Institute for Social Development (UNRISD) (2010) Combating poverty and inequality. United Nations Research Institute for Social Development (UNRISD), Geneva, Switzerland, 360p
USAID (2008) Nigeria biodiversity and tropical forestry assessment: maximizing agricultural revenue in key enterprises for targeted sites (markets). United States Agency for International Development (USAID), Nigeria, 90p
Wikipedia (2019) Social protection
World Bank (2010) Nigeria Gini index. The world bank trading economics. http://iresearch.worldbank.org/PovcalNet/index.htm
World Bank (2016) "Who are the poor in the developing world?" Policy research working paper 7844, background paper. Poverty and shared prosperity report 2016: taking on inequality
Yahaya U (2015) Bio-ethanol production from Eucalyptus wastes. Lambert Academic publishing, 102p

John E. Ochi is a Professor of Agricultural Economics in the Department of Agricultural Economics, Abubakar Tafawa Balewa University, Bauchi, Nigeria. His area of specialization is Production and Environmental Economics, in which he has worked extensively and published locally and internationally for over 30 years.

Ezekiel Y. Zaman is a Research Fellow, at the Trial Afforestation Research Station, Afaka Kaduna State, which is an affiliation of Forestry Research Institute of Nigeria, Ibadan, Nigeria.

Potential of Baobab (*Adansonia digitata* L.) in Adaptation to the Environmental Change

Taisser H. H. Deafalla

Abstract In recent years, the importance of natural resources in supporting rural livelihoods all over the world was increasingly being recognized in national and international policy. However, human well-being relies on our ability to sustainably exploit these resources. Approaches to development are, therefore, required to enable income generation from natural resources while at the same time supporting their effective conservation. This research investigates the importance of baobab tree in Non-Timber Forest Product and adaptation to Environmental Change (EC). It also highlights the conflict between national development efforts and a responsible approach to natural resource conservation. This is achieved using Nuba Mountains of Sudan as a case study. A semi-structured interview with 224 household heads was conducted. Furthermore, Rapid Rural Appraisal (RRA) based on free listing and key informant techniques were applied. The qualitative and quantitative techniques were used to analyze the socio-economic data. The study finds that drawing on baobab as a multiple value tree for livelihoods strengthens rural people's ability to deal with, and adapt to, both EC and extreme events. The key to facing the impact of EC is to develop viable policy responses and create dynamic innovative research, strategies, management and policies which focus on local communities to avoid the hazard of marginalizing those who rely on natural resources for subsistence and income generation.

Keywords Baobab tree · Environmental changes adaptation · Innovative research and strategies · Nuba mountains

1 Introduction

Despite international efforts, environmental change is still one of the most important security, climatic and developmental challenges facing humanity, especially in developing countries (Deafalla 2019). In recent years, the importance of natural resources,

T. H. H. Deafalla (✉)
Institute of Photogrammetry and Remote Sensing, University of Dresden, Dresden, Germany
e-mail: taisserhassan@yahoo.com

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_19

particularly Non-Timber Forest Products (NTFPs), in supporting rural livelihoods all over the world was increasingly being recognized in national and international policy (Cottray et al. 2006; Ratner et al. 2017). NTFPs play an indispensable role in the daily lives and overall well-being of rural and urban people, all over the world. As per the Food and Agriculture Organization (FAO) estimates in developing countries, 80% of the communities use NTFPs to meet their health and nutritional needs (FAO 2018). A large number of rural people, particularly those living in forested areas, depend on NTFPs for various needs. At the subsistence level, NTFPs are major sources for food, medicines, fodder, gums, fiber and construction material (Shackleton and Shackleton 2005; KSLA et al. 2005; Ahenkan and Boon 2011a; Akanni 2013). These products are more accessible to the poor (Saxena 2003; Deafalla et al. 2012). Furthermore, many of NTFPs are important traded commodities at local, national, regional and international levels, providing employment and income at each level (Marshall et al. 2003; Ahenkan and Boon 2011a; Deafalla et al. 2013). In developing countries alone, they provide around 17 million full-time jobs in the formal sector and another 30 million in the informal sector. Moreover, they provide 13–35% of all rural non-farm employment (Duong 2008; Abdulla 2013) and are a significant part of the economy of many countries, especially in sub-Saharan Africa, where they contribute to foreign exchange earnings (Ahenkan and Boon 2011b; Uduji and Okolo-Obasi 2019). In Sudan, for example, over 13% of the foreign exchange earned is generated from the Gum Arabic trade alone (Tieguhong and Ndoye 2004). In addition, NTFPs constitute a poverty trap, a safety net or a potential, but an underutilized resource for rural development and poverty alleviation (Belcher 2005; KSLA et al. 2005; Marshall et al. 2006; Ahenkan and Boon 2010; Deafalla 2011; Deafalla et al. 2014). Moreover, they play a significant role in supporting biodiversity and conservation objectives (FAO 1995; Charlie and Sheona 2004; Marshall et al. 2006; Solomon 2016) as they can be harvested by using simple improved technologies with relatively little impact on the forest environment (Myers 1988; Neumann and Hirsch 2000; FAO 2008; Ahenkan and Boon 2011a).

In recent years, *Adansonia digitata* L. (baobab) has started to gain considerable importance in the world due to the exponential development in the use of baobab in many industries and medicine. Besides, the use of baobab as food and drink is becoming more popular. In addition to that, baobab is developing a good market value, as well; public awareness is increasing about their socio-cultural use (Sulieman and Eldoma 1994; Deafalla 2012; Deafalla et al. 2014).

Adansonia digitata L. (Fig. 1) is an emblematic, culturally important and physically majestic tree. It is a truly multipurpose tree and contributes significantly to the livelihoods in Africa as a source of food, fiber and medicine (Wickens 1982; Codjia et al. 2001; Sidibe and Williams 2002; Chadare et al. 2009; De Caluwé et al. 2010a). For example, its roots are boiled and eaten in many parts of Africa in times of famine (Bosch et al. 2004; Deafalla 2012). In Sudan, it is made into a milk-like drink called 'gubdi' (Bosch et al. 2004). The powdered fruit flesh is added to cold liquid, thus preserving vitamins. In coastal Kenya and Tanzania, the pulp-coated seeds are colored and sugar-coated and sold as sweets (Bosch et al. 2004). The seeds are used to adulterate groundnuts and may be used as a coffee substitute. In Africa and India,

Fig. 1 Baobab tree

its leaves are used either fresh or as a cooked vegetable or dried and powdered as an ingredient of soups and sauces (Obizoba and Amaechi 1993; Yazzie et al. 1994; Kabore et al. 2011; Rahul et al. 2015). According to Elasha et al. (2009) and Deafalla (2012), through the experience of forest communities, forestry professionals have recently rediscovered the great importance of baobab (ranging from food, drinks, flavors and medicines) for meeting people's needs.

Scientific research has suggested that baobab can help communities meet their needs without destroying the forest resource (Deafalla et al. 2012). Approaches to development are, therefore, required that enable incomes to be derived from natural resources while supporting the effective conservation of these resources. There is hope that forest-dependent communities can gain new income-generating opportunities with minimal environmental cost. To offer a long-term source of income, baobab production will still require careful planning, management and monitoring. Researches regarding baobab harvesting and commercialization are still relatively recent and numerous of the datasets with more details necessary for a thorough analysis of these questions are still lacking (Rajchal 2006; Deafalla 2012). Therefore, tools are needed that could be used to direct external support to those areas with the highest potential for success. The current research uses Nuba Mountains, which represent a rich natural heritage and have one of the most rapidly growing economies of Sudan, as a case study.

2 Study Site

The study area is located in south Kordofan States. It lies between latitudes 10° and 13° N and longitudes 29° and 33° E (Fig. 2). It is composed of five provinces (Kadugli, Rashad, Abu Gubeiha, Talodi and El Dilling). It covers an area of approximately 141,096 km^2 (Fig. 1). The region has a varying climate, ranging from semi-desert in the north to rich savanna in the south. Annual rainfall ranges from less than 50 mm on the northern border to more than 800 mm on the southern border. The rainy season varies from about five months or less, with rains occurring between May and October.

The average daily temperature ranges from 10 to 35 °C with an annual variation of 15 °C. April to June is the hottest period, and December to February is the coldest. Wind direction differs according to seasons: northeast in winter and southwest in summer (El Tahir et al. 2010). Total population of the Nuba Mountains in 2008 was 1.3 million distributed into 120,986 households (CBS 2009). Livelihood activities are agro-pastoralism, nomadic pastoralism and rain-fed agriculture; both traditional farming for subsistence and mechanized farming for commercial operations. A third source of livelihood is related to natural forests in the form of woody and non-woody production derived from various tree species (UNDP 2006).

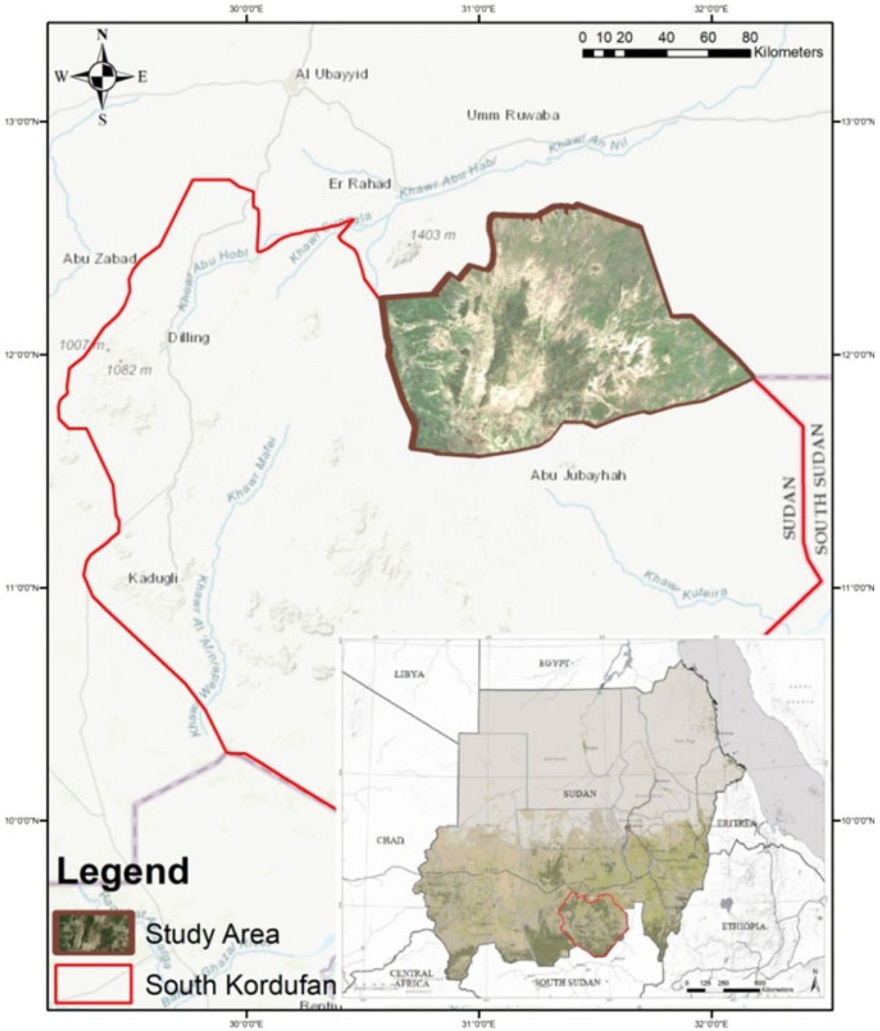


Fig. 2 Location of the study area. *Source* DIVA-GIS, developed by the authors

3 Research Methods

3.1 Socio-economic Data

Data Collection

Human, social and financial data were collected through social survey of households. Stratified sampling was used to represent different geographical areas and different income groups. This was to ensure better precision and save time, effort and monetary costs. The anthropometric survey was designed as a cluster sample (a representative selection of villages). Sixteen villages were randomly selected, three, ten and three villages in Rashad, Elabbassia and Abu Karshola localities, respectively. The total sample size was 224 questionnaires, 200 for heads of households of non-displaced respondents, while 24 for displaced people distributed among different units according to the Principle of Population Proportional to Size (PPS) in the selected sites.

Data Analysis

The collected information was coded, processed and analyzed, both qualitatively and quantitatively, using SPSS version 18.

Descriptive statistical analyses were applied to analyze data concerning social characteristics and perspectives of respondents about different aspects of the *Adansonia digitata* production and value chain activities. Spearman Rank-Order (SRO) correlation and Pearson Correlation Coefficient (PCC) were calculated to describe, test the relationship between these factors and estimate the probability of participation of households in collection of *Adansonia digitata* and the relative magnitude of such probabilities. This was based on different socio-economic/ecological factors that affect such activities, namely ethnicity, gender, education, age, primary occupation, duration of the primary occupation, war, migration, markets, etc.

4 Results and Discussion

A significant number of rural, tribal and forest-dependent communities derive a significant part of their food, nutrition, healthcare needs and income from the baobab tree. The tree is of primary significance for subsistence and/or income, at the household and village levels in those areas. The importance of baobab, in the study area, takes several forms of benefits. These can represent products that are collected directly for subsistence to enhance their direct needs of foods, medicine, raw materials for local industries or those for sale in order to earn an income. Roles of the baobab, in survival and poverty alleviation, were tackled in this research. Most of harvested baobab is used as food, medicine and nutritional supplements (Table 1). Furthermore, the study found that some baobab trees were consumed throughout the year by the rural households. These usually occur at the end of the dry season; they are also valued during peak periods of agricultural work from June to October and when less time is available for cooking also. As described in Table 1, baobab plays an important role in the prevention of malnutrition, where their importance is proved, in reducing the shortages suffered during the hunger periods of the war, as they help to even out seasonal fluctuations in the availability of food. Although the quantities of forest foods involved may be small, their nutritional contribution is often critical, especially when cultivated foods are unavailable.

Baobab has traditionally occupied an important position in the socio-cultural, spiritual and medicinal arena in the daily lives of people in the Nuba Mountains. Many of the poor people in the study area live in conditions where a nearby forest is the only accessible source of livelihood, where they attain their needs from direct collection of medical plants from forest or areas surrounding their settlements. Treatment of illness by traditional medicines is a fundamental part of health care in the study area, and it has played a vital role for centuries. The study found that this product was used in medication in all the households interviewed. Different parts of this plant, which included seeds, fruits, leaves and bark, were used.

4.1 Importance of Baobab in Food Security and Poverty Alleviation

In the Nuba Mountains, baobab is an important food and medicinal tree (Deafalla 2012), where its seeds, leaves, roots, flowers, fruit pulp and bark are edible. Leaves are used in the preparation of salad, while seeds are used as a thickening agent in soups and fermented for use as a flavoring agent. The fruit consists of pulp and large seeds embedded in the dry acidic pulp and shell. The pulp is used widely to make porridge and beverages as well as for different types of food. Various studies, such as Gruenwald (2009), De Caluwé et al. (2009), Kamatou et al. (2011) and Rahul et al. (2015), refer to baobab as a 'super fruit' based on its nutritional value (e.g., vitamin, fatty acid, mineral). Baobab fruit pulp has very high vitamin C content (280–300 mg/100 g), which is seven to ten times more than oranges, which contain 51 mg/100 g (Täufel et al. 1993; Vertuani et al. 2002). In addition, it contains a high percentage of ascorbic acid, about 337 mg/100 g (Eromosele et al. 1991; Gebauer et al. 2002; Gebauer 2003). Chadare et al. (2009) demonstrated that the consumption of 40 g of baobab pulp provided 100% of the recommended daily dose of vitamin C to pregnant women (19–30 years).

Baobab tree provides employment opportunities for youth, women and elderly members of households as baobab collection is the single most important secondary occupation in the area where 59% of displaced households and 36% of non-displaced households are involved. The results agree with Deafalla (2012) who has pointed out

Table 1 Uses of *Adansonia digitata*

Product	Status	1	2	3	4	5	6	1 and 2	1 and 3	2 and 3	7	8
Adansonia digitata	Non-displaced households (%)	3.6	6.4	20	0	0.7	0	2.1	6.4	40.7	17.9	2.1
	Displaced households (%)	3.1	95	20	0	0.7	0	19.2	4.8	39.4	1.9	1.9

Legend: (1) Foods, (2) Drinks, (3) Medical Uses, (4) Animal Feeding, (5) Raw materials for local industries, (6) Cosmetic, (7) Other and (8) For All Uses that NTFPs could play a vital role in rural areas, where resources are meager and the weaker sections of the community cannot migrate to seek employment elsewhere or cannot engage in labor demanding activities. Both women and children, often from the poorest households, can obtain a major source of their subsistence from a diverse set of forest products, including many of the same products sold for cash income. Baobab provided cash-generating opportunities for the women (14.30%), elderly and children (25.7%), where all members of the household participate in collection of NTFPs (21.4%). It is important to note that head of the household plays an important role in this collection.

4.2 Role of Baobab in Medical Uses

Medicinal plants play an important role in the daily life of many cultures, especially in rural areas where a vast majority has no access to modern medicine and relies heavily on traditional cures (Deafalla 2019). However, there is a lack of information regarding traditional medicinal uses and prescription of plants in the country, which threatens their existence. Knowledge about this is orally transmitted through generations, and even nowadays, documentation is poor. The traditional knowledge of medicinal plants is facing serious threat due to the strong influence of modern culture and Western worldview (Deafalla 2019) which has eroded traditional values among young people (Deafalla 2011). Moreover, they are largely neglected by governments and scientists.

Throughout Africa, baobab is held in awe by most indigenous people, some even considering it bewitched (Wickens and Lowe 2008). Various parts of the plant are used as a panacea to treat almost any disease, but specific documented uses include its use as an immunostimulant and for the treatment of malaria, tuberculosis, fever, microbial infections, diarrhea, anemia, dysentery, toothache, etc. (El-Rawy et al. 1997; Wyk and Gericke 2000; Brendler et al. 2003; Tapsoba and Deschamps 2006; Wickens and Lowe 2008; De Caluwé et al. 2010a; Nguta et al. 2010; Kamatou et al. 2011). The way baobab is used varies from one country to another. For example, a decoction of the bark is used in Congo to bathe rickety children, while in Tanzania, it is used to treat toothache (Bosch et al. 2004). Meanwhile, in Ghana, the bark is used as a substitute for quinine (Dweck 1996). Bark and fibers lining the fruit husk are used to treat amenorrhea. The pulp is used in the treatment of hot flushes in Benin (Wickens and Lowe 2008). In Messina, the powdered seed is given for hiccough in children (Jayaweera 1981). A root decoction is taken with food in Sierra Leone for strength (Bosch et al. 2004). In Malawi, baobab juice, called 'dambedza,' is served as a cure for hangovers and against constipation. In Zambia, a root infusion is used to bathe babies to promote a smooth skin (Wickens 1982). In the study site, almost all parts (fruits, leaves, bark and seeds) of the tree are used in traditional medicine. Several parts of the plant have anti-oxidant and anti-inflammatory properties (De

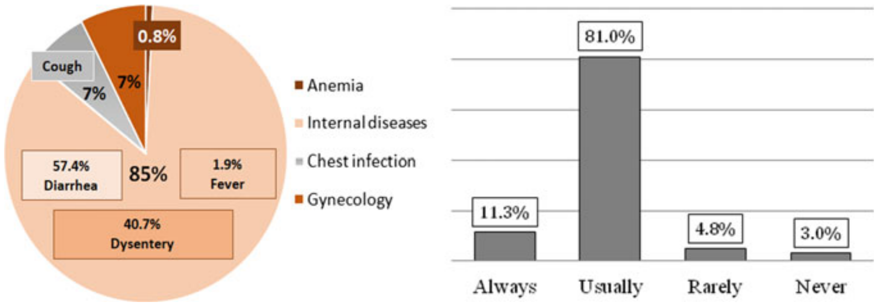


Fig. 3 Diseases treated by *Adansonia digitata* L. and its frequency of uses for treatment

Caluwé et al. 2010b; Kamatou et al. 2011; Rahul et al. 2015; Usman and Asan 2017). Seed oil is renowned for healing attributes and has been used by practitioners of traditional medicine, in particular, for cleansing the uterus and other gynecological uses. An aqueous extract of the fruit is used to treat anemia and microbial infections such as diarrhea and dysentery (Fig. 3). The leaves and fruit pulp are used as febrifuge to treat fever as well as an immune stimulant. The study indicated that fruit uses in cough treatments were mainly for displaced people.

4.3 Other Contributions of Baobab in Study Site

Besides using the tree for shade, it is used as raw material for local industries (Fig. 4). The tree is characterized by a large amount of bark and fiber and hence used in manufacturing ropes. Fiber is obtained either from the trunk, branches or root bark, by removal of the outer bark after cutting it. Then, the fiber is placed in water for two or three days to remove the juice. After removing from water, it is exposed to the air, to evaporate water, and then used to make ropes. These ropes are used in weaving local beds (local name: *Angraeb*) and chairs (local name: *Banbar*), connecting/tying animals, strings, cords for musical instruments, snares, loin cloths, sacking, baskets, mats, waterproof hats and buckets and halters for camels. In the study area, baobab plays a vital role in water storage during the dry season, where a hollowed trunk is carved out in 3–4 days. A medium-sized tree holds 400 gallons, while a large tree could contain about 3000 gallons, and the inner fibers in the trunk help to purify the water. The water stored in them is said to remain sweet for several years, if the hollow is kept well closed. Baobab trees have a specific importance to local people in the study site; it is the place in the village where the elders meet to resolve problems.

Fig. 4 Local industry from baobab

4.4 Value Chain of **Adansonia digitata** *L. in Study Site*

Baobab value chain can be broken down into several sub-sets of activities (Fig. 5), including production, collection, processing, storage, transportation, marketing and sale. The current finding agreed with Deafalla (2012), who have indicated in their review the sub-set activities of NTFP commercialization and value chain.

The study finds that the largest quantity collected in study site was from *Ziziphus spina-christi,* followed by *Adansonia digitata* L. This is due to the location of their campus which is in the high mountains where rich forest resources are available and accessible.

The quantities collected by displaced household were higher compared with non-displaced household (Table 2). The time spent in a trip of collection of *Adansonia digitata* L. took about 3 h. This is directly related to difficulties of collection due to long distance to the collection sites and harsh topography. For non-displaced households, distance to place of collection of baobab tree products ranged from 2.32 to 2.78 km, while the situation differed with displaced households, where the distance

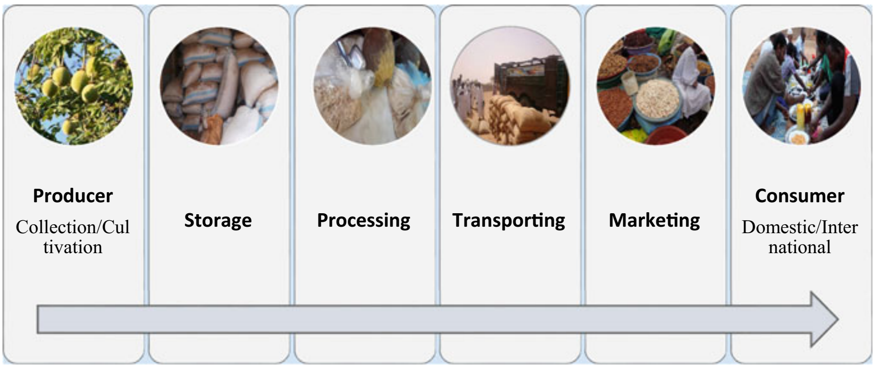


Fig. 5 Production-to-consumption *Adansonia digitata* L. systems

Table 2 Quantity of *Adansonia digitata* L. collected, consumed and sold (kg)

Product	Status	Quantity collected (kg)	Quantity consumed (kg)	Quantity sold (kg)
Adansonia digitata L.	Non-displaced households	73,480	53,510	19,970
	Displaced households	35,578	1561	34,017

to place of collection of these trees ranged from 0.52 to 1.50 km. That was due to the fact that they collected the products during their trip from their camps in mountains to/from towns.

The study found that no advanced harvesting techniques were used in the study area. Simple tools and no external inputs were used. In addition, most of respondents did not use any tools for harvesting of baobab trees. That agreed with Duong (2008), who described the positive impact of NTFPs to forest conservation as 'harvesting of NTFPs usually has a lower impact on the forest ecosystem than timber harvesting and can provide an array of social and economic benefits, particularly to community operations, and can therefore be an important component of forest ecosystem management.'

Most respondents (89.9%) did not store or do any processing after the collection. Meanwhile, 10.1% of respondents store the fruits and crush them to powder for selling. The main reasons for storing the products were conservation, realization of higher prices and for own later use (Fig. 6).

The source of expertise in collection, handling and storage methods and the use of product are tradition. In addition, 91% of respondents did not participate in any extension service programs or capacity building workshops to deal with management of product. A need arises for improving existing tools, introducing improved ones, training and availing better storage and utilization facilities. Investments in value-added processing and transportation are badly needed. Most important, however, is the adoption of management systems that sustain the resource base as well as the yield.

The main problems facing the collection were the war (15.2%), followed by long distance (13.3%), natural climatic conditions (7%), lack of transportation (7%) and

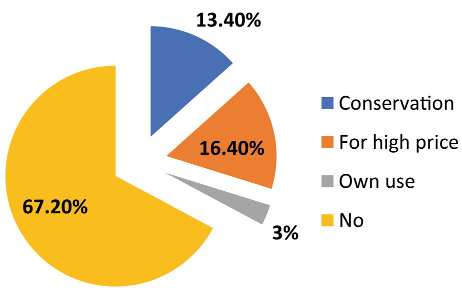


Fig. 6 Reasons of NTFPs storing

'all of these reasons' (4%). In contrast, 53.2% of households responded that they are not facing any problems in the collection of these products.

On the other hand, a considerable number of households preferred to purchase the baobab due to their inability to collect, due to reasons of security (3.2%), health reasons (22.3%), customs and traditions (16.5%), far distances to the nearest forest (3.2%) and 54.8% have no interest in collecting these products. Elabbassia, Rashad and Um Baraka were the main markets for baobab's buyers followed by village's market and Tabassa.

Haulage of product to the point of delivery in markets is traditionally carried out by various types of transportation: truck (lorry), bicycle, cart (caro), donkey and by foot. The study found that trucks are the main transportation method used in normal times as well as in times of rain or war, which fits well with the topographic and soil condition in the study area. However, the problems with trucks are the poor, or absent in some cases, road links. Most of the villages in the study site were completely cut-off from the rest of the country during the rainy season, due to the muddy soil type which inhibits vehicles and for the availability of trucks that becomes scarce due to looting and land mines in the times of war. Donkeys or self-transport is used when the quantity of product is small. Transport cost was about 1.8–3.65 (Euro) for every sack and sometime about €4.55 to €5.5.

In Nuba Mountains, fruits of this tree are found in most local markets throughout the year. Elabbassia market is the main market for it. This is directly related to geographical location, followed by Um Baraka, the second-biggest market in the study site, after Rashad market and with limited quantities in the village market. In the study area, the market of baobab is extremely disordered and unstructured. Due to lack of direct access to markets, forest dwellers collect *Adansonia digitata* L. and sell it to local traders, who in turn sell it to the urban center, reducing their share of the income. In general pattern in much of the literature on NTFPs, such as Neumann and Hirsch (2000), Deafalla (2012) and Amusa et al. (2017), they indicated that the relationships between collectors and traders, particularly the middlemen or intermediaries, are economically exploitative. In this study, the distribution channel from forest collector to urban wholesaler consists of 3–5 agents who, in many cases, shell out loans as advance payment for baobab. They have great influence on the marketing process as they are able to provide local people with essential resources and services. On the other hand, these intermediaries hustle the tribals, cheating them on weights and rates as the tribals mostly count in traditional scales and are unfamiliar with the metric measure. The tribals have to sell their material as they need the money to buy weekly supplies. There were at least four levels of intermediaries between the collectors/gatherers in Nuba Mountains and processing center or the main markets in Khartoum state. Ghosal (2013) reported that marketing of NTFPs through formal channels is a complicated task in the Global South because of the lack of suitable infrastructure and the influence of intermediaries. Strengthening the formal marketing process, on the one hand, can reduce the exploitation of forest products while improving the socio-economic status of forest fringe villagers.

Investigation of the marketing channels of *Adansonia digitata* L. has shown that pricing of products is largely decided by the market intermediaries. Although our study did not explore the profit margin distributed along the market chain, several related studies have shown that collectors have the smallest profit margin in the market chain (Mhapa 2011; Piya et al. 2011). Furthermore*,* collectors are unorganized and dispersed, where trading is done individually. They lack knowledge and skills and marketing information to gain leverage. There is also a lack of related business assets such as storage and transport (Ahenkan and Boon 2011b). This leads to low returns and exploitation of baobab collectors. The present findings agree with the report of Kar and Jacobson (2012) working on trade in NTFPs in Chittagong Hill Tracts of Bangladesh and are consistent, as well, with Amusa et al. (2017) who studied the socio-economic factors influencing marketing of NTFPs in south-western Nigeria.

Intermediaries place demand with the collectors before *Adansonia digitata* L. collection and advancing payment in form of credits. This has been observed to tie the collectors to the apron-spring of the traders through debt or patron-client type relationships, and this agreed with Neumann and Hirsch (2000). Therefore, Piya et al. (2011) suggested that shortening the marketing chain would leave more of the NTFPs value in the hands of the collectors. Most respondents are quite aware of the shortcomings of the system, but did not have the capital or the connections to remedy the situation.

Generally, market constraints often reduce the bargaining power of the poor harvesters supplying the products (Bhattarai et al. 2003). Insufficient and poor transportation services, as well as product distribution within the forest, were the major constraints for the collection and marketing. It is important to note that despite the significant values of the products, there is a variation in price. The market value of *Adansonia digitata* L. not only varies with season, but also with the availability of the products and demand.

4.5 Heterogeneous Factors Affecting Baobab Marketing

The study found that there were socio-economic factors which influenced the marketing of baobab. Going by the marketing experience factor, the main member who sells baobab product was head of the family. In many developing countries, the only way women in remote rural areas can earn cash is only by trading NTFPs in the local markets. However, women's role in trading and marketing forest produce is often not part of formal value chains and, therefore, overlooked. In the study site, trading and marketing opportunities for women remained restricted by the rigid cultural patterns, tradition and social norms, particularly among women between 15 and 35 years of age. Unfortunately, the low profile of women in trading and marketing means initiatives to promote trade in baobab products do not benefit women (Neumann and Hirsch 2000; Hasalkar and Jadhav 2004; Schreckenberg and Marshall 2006).

Furthermore, this product is sold and bought many times, adding value at each step before reaching the consumer and the end user. In general, the relationship among actors in the value chain, from the collectors, middlemen, traders to wholesalers, varies from one state to the other. In addition, the roles and returns on profit to actors in the chains changed over the time of study and were mainly related to inflation and the Sudanese currency.

5 Conclusion

The research highlighted the significant role of *Adansonia digitata* L. in contributing to Nuba Mountains' economic development, food security and environmental health. The study showed that drawing on *Adansonia digitata* L. for livelihoods strengthens rural population's ability to deal with, and adapt to, both EC and extreme events. Baobab, being a multiple value tree, contributes to the well-being of rural households, particularly the poor, in terms of food and nutrition security, health and subsistence. And it shows great potential in providing multiple needs, a fact that is clearly supported by the current findings.

Innovative research and development are needed to encourage the investments on baobab through maintenance and use of indigenes knowledge, mechanisms for its sustainable harvesting of fiber and bark through trainers involving community and NGOs, industry and gene bank development.

In addition to that, securing sustainable baobab supply by conserving the species, improving its market value through pre- to post-processing, expanding marketing opportunities through better value chain and supply chain mechanism and protecting baobab uses and users' knowledge will go a long way in improving environmental benefits and ecosystem stability.

References

Abdulla AM (2013) Contribution of non-timber forest products to household food security: the case of Yabelo Woreda, Borana Zone, Ethiopia. Food Science and Quality Management, ISSN 2224-6088 (Paper) ISSN 2225-0557 (Online), vol 20. pp 1–13

Ahenkan A, Boon E (2010) Commercialization of non-timber forest products in Ghana: processing, packaging and marketing. Food Agric Environ 8:962–969

Ahenkan A, Boon E (2011a) Non-timber forest products (NTFPs), clearing the confusion in semantics. J Hum Ecol 33(1):1–9

Ahenkan A, Boon E (2011b) Improving the supply chain of non-timber forest products in Ghana. In: Supply chain management—new perspectives. InTech, pp 443–458

Akanni KA (2013) Economic benefits of non-timber forest products among rural communities in Nigeria. Environ Nat Res 3(4):19–26

Amusa TO, Jimoh SO, Azeez IO (2017) Socio-economic factors influencing marketing of non-timber forest products in tropical lowland rainforests of south-western Nigeria. South Forest J For Sci 1–8

Belcher BM (2005) Forest product markets, forests and poverty reduction. Int Forest Rev 7(2):82–89

Bhattarai B, Ojha H, Banjade MR, Luintel HI (2003) The effect of NTFP market expansion on sustainable local livelihoods—a case of Nepal. Discussion paper. Forest Action Nepal, Kathmandu

Bosch CH, Sié KA, Safa BA (2004) *Adansonia digitate* L. record from PROTA4U. In: Grubben GJH, Denton OA (eds) PROTA (Plant resources of Tropical Africa/Ressources végétales de l'Afrique tropicale). Wageningen, Netherlands. Available from: http://www.prota4u.org/search.asp. Accessed on May 15, 2016

Brendler T, Gruenwald J, Jaenicke C (2003) Herbal remedies. Medpharm GmbH Scientific Publishers (CD-ROM), Stuttgart, Germany, pp 10–21

Central Bureau of Statistics (CBS) (2009) Fifth Sudan national population and housing census. Census tables. Available online at www.cbs.gov.sd. Accessed on 1/7/2017

Chadare FJ, Linnemann AR, Hounhouigan JD, Nout MJ, Van Boekel MA (2009) Baobab food products: a review on their composition and nutritional value. Crit Rev Food Sci Nutr 49:254–274

Charlie S, Sheona S (2004) The importance of non-timber forest products in rural livelihood security and as safety nets: a review of evidence from South Africa. S Afr J Sci 100:58–664

Codjia JTC, Fonton BK, Assogbadjo AE, Ekue MRM (2001) Le baobab (*Adansonia digitata*) Une Espèce à Usage Multiple au Bénin. Cecodi, CBDD, Veco, SNV, FSA, p 45

Cottray O, Miles L, Newton A (2006) Non-limber forest products in Uganda spatial tools supporting sustainable development. UNEP-WCMC, Cambridge, UK, pp 4–32

De Caluwé E, Halamová K, Van Damme P (2009) *Tamarindus indica* L.—a review of traditional uses, phytochemistry and pharmacology. In: Juliani HR, Simon JE, Ho CT (eds) African natural plant products: discoveries and challenges in quality control. American Chemical Society symposium series 1021, American Chemical Society, Washington, D.C., USA

De Caluwé E, Halamová K, Van Damme P (2010a) *Adansonia digitata* L.—a review of traditional uses, phytochemistry and pharmacology. Afrika Focus 23:11–51

De Caluwé ED, Katerina Halamová K, Van Damme P (2010b) *Tamarindus indica* L.—a review of traditional uses, phytochemistry and pharmacology. Afrika Focus 23(1):53–83

Deafalla THH (2011) Contribution of non wood products to rural livelihood in South Kordofan State. M.Sc. thesis, University of Khartoum, Khartoum, Sudan, pp 6–45

Deafalla THH (2012) Non wood forest products and poverty alleviation in semi arid region. LAP LAMBART Academic Publishing GmbH & Co. KG, Germany, p 22. ISBN: 978-3-659-16411-8

Deafalla THH (2019) Integrative assessment and modelling of the non timber forest products potential in Nuba Mountains of Sudan by field methods, remote sensing and GIS. Ph.D. thesis. Submitted to Faculty of Environmental Sciences, University of Dresden, June 2019, Germany, 319 p

Deafalla THH, Dafa-Alla DM, Eltayeb AM (2012) Potentiality of non wood forest products to poverty alleviation and food security in Nuba Mountains, Sudan. In: Symposium of agricultural sustainable development and chain. Sudan Research Collaboration, Yangshuo, China

Deafalla THH, Dafa-Alla DM, El-Abbas MM (2013) Impacts of non timber forest products. In: SLU, IUFRO, the Swedish Research Council for Environment Agricultural Sciences and Spatial Planning and COST (eds) Sustainable forest management. COST action FP0804 decision support systems for sustainable forest management. Proceedings of FORSYS 2013 conference, 24–26 April, Umea, Sweden

Deafalla THH, Dafa-Alla DM, El-Abbas MM (2014) The importance of non wood forest products for rural livelihoods: the case of South Kordofan state, Sudan. In: Behnassi M, Shahid AA, Mintz-Habib N (eds) Science, politics of modern agricultural system: global context to local dynamics of sustainable agriculture, Chap 22, pp 323–332

DIVA-GIS. http://www.diva-gis.org/gdata

Duong NH (2008) The role of non timber forest products in livelihood strategies and household economics in a remote upland village in the upper river basin, nghe the Phuong. J Sci Dev 88–98

Dweck AC (1996) Ethnobotanical plants from Africa part two. Cosmetics and Toiletries Magazine, 18 p

El-Rawy EM, Gergis SM, Bazaid S, El-Mougy SA (1997) The immunostimulant effect of *Adansonia digitata* on the immune response of chicken vaccinated with avian cholera vaccine. J Egypt Vet Med Assoc 57:959–970

El Tahir BA, Fadl KM, Fadlalmula AGD (2010) Forest biodiversity in Kordofan Region, Sudan: effects of climate change, pests, disease and human activities. Biodivers Conservancy 11(3–4):34–44

Elasha BO, Parrotta J, Adger N, Brockhaus M, Colfer CJP, Sohngen B, Dafalla T, Joyce LA, Nkem J, Robledo C (2009) Future socio-economic impacts and vulnerabilities. In: Seppälä R, Buck A, Katila P (eds) Adaptation of forests and people to climate change. A global assessment report. IUFRO world series, vol 22, pp 101–122

Eromosele IC, Eromosele CO, Kuzhkuzha DM (1991) Evaluation of mineral elements and ascorbic acid contents in fruits of some wild plants. Plant Foods Hum Nutr 41:151–154

FAO (2008) The state of food insecurity in the world 2008. Rome, pp 22–31

FAO (2018) About non-wood forest products. Towards a harmonized definition of non-wood forest products. Unasylva, Issue no 198. Available from: http://www.fao.org/forestry/nwfp/6388/en/. Accessed January 2, 2018

Gebauer J (2003) Ökophysiologie und Verwendungsmöglichkeiten der Wildobstarten *Adansonia digitata* und *Tamarindus indica* im Sudan. Ph.D. thesis. Landwirtschaftlich-Gärtnerischen Fakultät der Humboldt-Universität zu Berlin, 139 p

Gebauer J, El-Siddig K, Ebert G (2002) Baobab (*Adansonia digitata* L.): a review on a multipurpose tree with promising future in the Sudan. Eur J Hortic Sci 4:155–160

Ghosal S (2013) The role of formal marketing channels in NTFP business. J Sustain Forest 32(3):310–328

Gruenwald J (2009) Novel botanical ingredients for beverages. Clin Dermatol 27:210–216

Hasalkar S, Jadhav V (2004) Role of women in the use of non-timber forest produce: a review. J Soc Sci 8(3):203–206

Jayaweera DM (1981) Medicinal plants used in Ceylon part 1. National Science Council of Sri Lanka, Colombo

Kabore D, Sawadogo-Lingani H, Diawara B, Compaoré C, Dicko MH, Jakobsen MA (2011) Review of baobab (*Adansonia digitata*) products: effect of processing techniques, medicinal properties and uses. Afr J Food Sci 5(16):833–844

Kamatou GPP, Vermaak I, Viljoen AM (2011) An updated review of *Adansonia digitata*: a commercially important African tree. S Afr J Bot 77(4):908–919

Kar SP, Jacobson MG (2012) Market constraints in NTFP trade: household perspectives in Chittagong Hill Tracts of Bangladesh. Int For Rev 14:50–61

(KSLA, AAS and FAO) Royal Swedish Academy of Agriculture and Forestry (KSLA), African Forest Research Network (AFORNET) at the African Academy of Sciences (AAS) and Food and Agriculture Organisation of the United Nations (FAO) (2005) Lessons learnt on sustainable forest management in Africa. Policy briefs no 10

Marshall E, Schreckenberg K, Newton AC, Bojanic A (2003) Researching factors that influence successful commercialisation of non timber forest products (NTFPs). Lyonia 5:61–72

Marshall E, Rushton J, Schreckenberg K, Arancibia E, Fabrice Edouard F, Newton A (2006) Practical tools for researching successful NTFP commercialization: a methods manual, 72 p. Available from: https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/3906.pdf

Mhapa PI (2011) Trade of non timber forest products and its contribution to the livelihood in Njombe District, Tanzania. M.Sc. thesis, Sokoine University of Agriculture, Tanzania

Myers N (1988) Tropical forests: much more than stocks of wood. J Trop Ecol 4:209–221

Neumann RP, Hirsch E (2000) Commercialization of non-timber forest products: review and analysis of research. CIFOR, Bogor

Nguta JM, Mbaria JM, Gakuya DW, Gathumbi PK, Kiama SG (2010) Kiama antimalarial herbal remedies of Msambweni, Kenya. J Ethnopharmacol 128(2):424–432

Obizoba IC, Amaechi NA (1993) The effect of processing methods on the chemical composition of baobab (*Adansonia digitata* L.) pulp and seed. Ecol Food Nutr 29:199–205

Piya L, Maharjan KL, Joshi NP, Dangol DR (2011) Collection and marketing of non-timber forest products by Chepang Community in Nepal. J Agric Environ 12:10–21

Rahul J, Jain MK, Singh SP, Kamal RKK, Naz AA, Gupta AK, Mrityunjay SK (2015) *Adansonia digitata* L. (baobab): a review of traditional information and taxonomic description. Asian Pac J Trop Biomed 5(1):79–84

Rajchal R (2006) Analytical review of the definitions of non timber forest product. Available from: www.forestrynepal.org/article/rrajchal/456. Accessed on April 24, 2013

Ratner BD, Meinzen-Dick R, Hellin J, Mapedza E, Unruh J, Veening W, Haglund E, May C, Bruch C (2017) Addressing conflict through collective action in natural resource management. Int J Commons 11(2):877–906

Saxena NC (2003) Livelihood diversification and non-timber forest products in Orissa: wider lessons on the scope for policy change? ODI working paper no 223. Overseas Development Institute, London, UK

Schreckenberg K, Marshall E (2006) Women and NTFPs: improving income and status? In Marshall E, Schreckenberg K, Newton AC (eds) Commercialization of non timberforest products: factors influencing success. UNEPWCMC, Cambridge, 136 p. Available from: http://quin.unep-wcmc.org/forest/ntfp/gender.cfm?displan=eng

Shackleton SE, Shackleton CM (2005) The contribution of marula (Sclerocarya birrea) fruit and fruit products to rural livelihoods in the Bushbukridge district, South Africa: balancing domestic needs and commercialisation. Forest Trees Livelihoods 15(1):3–24

Sidibe M, Williams JT (2002) Baobab. *Adansonia digitata* fruits for the future, vol 4. International Centre for Underutilised Crops, Southampton, UK, p 100

Solomon MM (2016) Importance of non timber forest production in sustainable forest management and its implication on carbon storage and biodiversity conservation in case of Ethiopia. J Biodivers Endanger Species 4:160. ISSN: 2332-2543. http://doi.org/10.4172/2332-2543.1000160

Sulieman MS, Eldoma AMA (1994) Marketing of NWFP (excluding the Gum Arabic) in the Sudan. Forest products consumption survey: topic specific study report no. 14. Forests National Corporation, Ministry of Agriculture Animal Wealth and Natural Resources, FAO, Khartoum, Sudan

Tapsoba H, Deschamps JP (2006) Deschamps use of medicinal plants for the treatment of oral diseases in Burkina Faso. J Ethnopharmacol 104:68–78

Täufel A, Ternes W, Tunger L, Zobel M (1993) Lebensmittel-lexikon, 3. Aufl., 1500 S, vol 337. Behr's Verlag, Hamburg, Gebunden DM 229, p 78

Tieguhong JC, Ndoye O (2004) Development of trade and marketing of non-wood forest products for poverty alleviation in Africa. Paper presented at the workshop on lessons learnt on sustainable forest management in Africa, Uppsala, Sweden, 18–22 Oct

Uduji JI, Okolo-Obasi EN (2019) Youth empowerment in non-timber forest products (NTFPs) of sub-Saharan Africa: the role of corporate social responsibility in Niger Delta, Nigeria. J Enterprising Commun People Places Glob Econ. https://doi.org/10.1108/JEC-08-2017-0066

United Nations Development Programme (UNDP) (2006) Pastoral production systems in south Kordofan (study 2), Sudan, pp 8–13

Usman IA, Asan TV (2017) Influence of different pretreatments on seed germination and growth rate of *Adansonia digitata* (Alert) seedlings. J Res For Wildl Environ 9(2):8–14

Vertuani S, Braccioli E, Buzzoni V, Manfredini S (2002) Antioxidant capacity of *Adansonia digitata* fruit pulp and leaves. Acta Phytotherapeutica 5:2–7

Wickens GE (1982) The baobab—Africa's upside-down tree. Reprint from Kew Bull 37(2):171–202

Wickens GE, Lowe P (2008) The baobabs: pachycauls of Africa Madagascar and Australia. Springer, UK, 498 p

Wyk BE, Gericke N (2000) People's plants—a guide to useful plants of Southern Africa. Briza Publications, Pretoria, 352 p

Yazzie D, VanderJagt DJ, Pastuszyn A, Okolo A, Glew RH (1994) The amino acid and mineral content of baobab (*Adansonia digitata* L.) leaves. J Food Compost Anal 7:189–193

Dr. Deafalla is a Crisis Mapper and Coach for human development at many national and international NGOs. Currently, she is a senior researcher at the Institute of Photogrammetry and Remote Sensing, Faculty of Environmental Sciences, University of Dresden, Germany. She has a professional experience in the fields of the forestry, environmental change, and rural development where she worked with many local and international organizations. Moreover, Dr. Deafalla has participated in many international conferences and workshops and she has many scientific publications related to environmental change.

Realizing Food Security in Saline Environments in a Changing Climate: Mitigation Technologies

Jibran Tahir, Azaiez Ouled Belgacem, and Rubina Jibran

Abstract The evolution of life on earth is increasingly shaped by dramatic climatic changes. These have consequently affected life-supporting factors on our planet, including air, light, soil, and water. In the last 150 years, humanity-driven changes in climate have promoted the salinization of agricultural lands. Salt accumulation in groundwater coupled with extended periods of droughts, a rise in sea levels, and deforestation are key processes that deteriorate agricultural lands needed for food production. The impact of salinization is significant and cripples farming communities, threatens economic and food independence and habitability of lands, and challenges the survival of planetary biota. In this chapter, we provide a comprehensive review of major progress made in soil management, plant genetics, molecular sciences, and indoor farming given their importance in the quest to reduce the impact of salinization on crop production.

Keywords Halophytes · Rhizosphere · Salt-affected soils · Salt-tolerant plants · Sustainable niches · Urban agriculture

1 Introduction—Cracking Salinity

Global climatic changes, particularly high temperatures and unpredictable rainfalls in combination with high water usage in agricultural areas, are bringing dramatic changes to plant life on earth. Through these changes, a higher concentration of soluble salts is being accumulated in groundwater and in the topsoil layers which

J. Tahir (✉) · R. Jibran
Terrestrial Biosciences New Zealand Limited, Auckland, New Zealand
e-mail: jibran.tahir@plantandfood.co.nz

The New Zealand Institute for Plant and Food Research Limited, Auckland, New Zealand

A. O. Belgacem
Sustainable Rangeland Management, Food and Agricultural Organization of the United Nations, Riyadh, Saudi Arabia
e-mail: Azaiez.OuledBelgacem@fao.org

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_20

support the crop root system. Soluble salts—including $CaCl_2$, NaCl, and $MgCl_2$—disrupt the osmotic potential of the soil water in the root zone, thereby limiting plant growth. Excess of Na^+ ions in soils, specifically at the cation exchange sites, can further deteriorate soil structure, instigating sodic soils, which are less permeable to water. The total amount of land that is now salinized across all continents has surpassed a billion hectares, including saline and sodic properties (Shahid et al. 2018). The saline, sodic, and saline-sodic soils are mostly found in South America, Africa, North and Central Asia, South Asia, and Australasia, where a significant part of the world's population is dependent upon local agriculture (Rengasamy 2006). Both salinity and drought stress reduce the ability of plants to uptake water, thus negatively affecting growth, carbon fixation, and yield. The UN Sustainable Development Goal 15 (Life on Land) specifically focuses on reducing the desertification of arable land, which is associated with occurring salt and drought stress and resulting in the loss of approximately 12 million hectares of farmland every year.

On a global scale, food production needs to be increased in the next 30 years; however, salinization directly threatens crop food production as well as livestock productivity. Salinization affects the types and volume of crops that could be grown, as well as the amount of food we can produce in affected regions. Regions at a greater risk of desertification are arid and semi-arid regions, areas that utilize groundwater for intensive farming, coastal regions, and inland regions situated far from rivers. Desertification may also be causing a further feedback effect on climate change, as the lack of plants on millions of hectares will affect the process of carbon fixation through reduced microbial activity associated with plant roots, as well as disrupt nutrient recycling and cause biogeochemical changes that are unidentified yet. How plants cope with such stresses is determined by a multitude of environmental factors such as day length, rainfall and seasonal changes, biotic and abiotic factors such as organic matter, microbial activity, soil pH, and metal toxicity, as well as plant genetic factors. Therefore, there is an urgent need to develop strategies for a way forward in terms of sustainable rehabilitation of salt-affected soils and implementation of technologies that can support farming on saline lands. In this perspective, we attempted to visualize the scientific progress and initiatives in various disciplines that are on pathways to mitigate the impact of salinization on crops and soil health and promote sustainable farming. We organized these different pathways in a mind map (Fig. 1), connecting the problem of salinization and the approaches for mitigating its impact on agriculture and food production.

From the mid of the twentieth century, scientific progress has been made in three scientific disciplines to reduce the effect of salt stress on crop production. The *first* approach can be referred to as 'sustainable niches,' where technologies associated with the soil and water management are implemented in combination with biological inputs to reduce salt stress, improve soil properties and biological characteristics of the rhizosphere, and consequently improve plant growth and crop yield. The *second* approach explores the genetic potential of various plant species to developing salt tolerance. This includes breeding for salt tolerance in major crops, employing forward and reverse genetic approaches to identify genes that promote salt tolerance in model plants and cereal crops, and investigating the genetics of salt-resistant plant species.

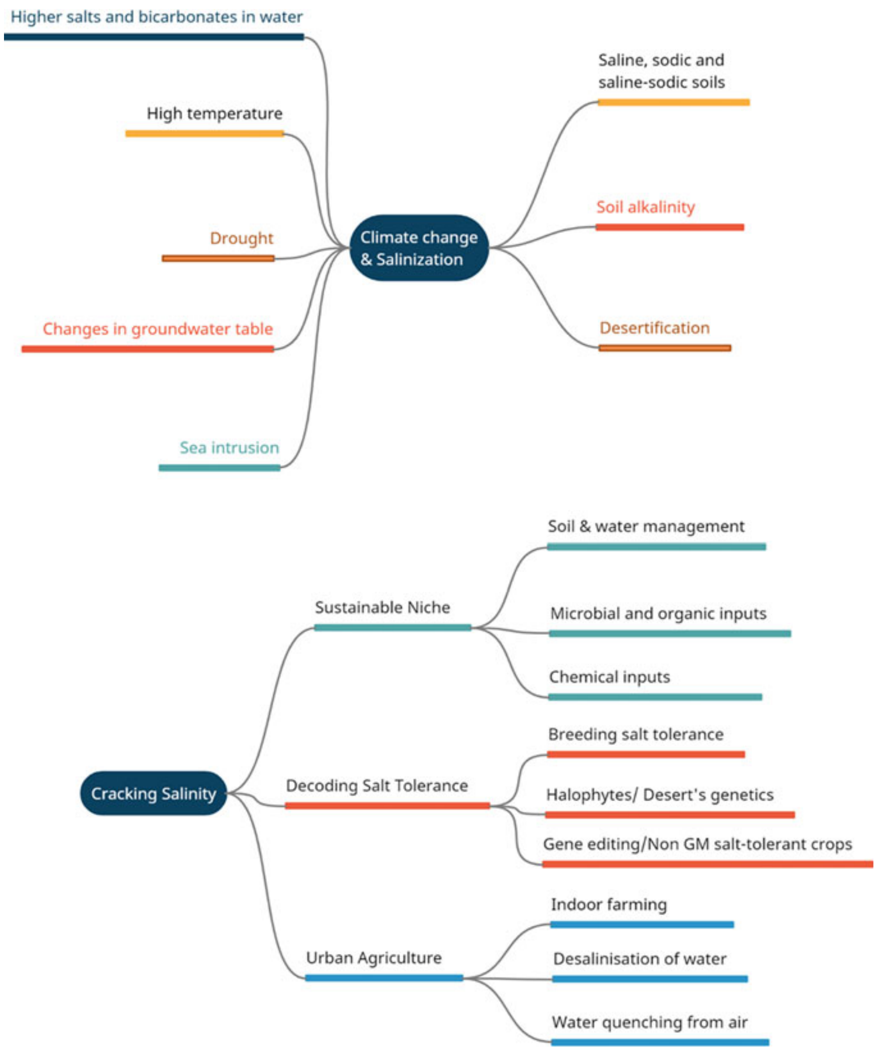


Fig. 1 Mind map of climate change and salinization and mitigating technologies. *Source* Developed by the authors

Finally, the *third* approach focuses on ways to avoid salt stress by means of urban agriculture. This involves the application of technologies such as desalinization of water using reverse osmosis, quenching clean water from the air to reduce water and salt stress in arid and dry regions, and indoor farming. In this chapter, we have navigated these approaches and their impact, as well as limitations of these paths in improving crop and food production.

2 Salty Rhizospheres—Physical, Chemical, and Biological Mitigation Technologies in Saline Environments

The impact of land salinization directly influences the biophysical properties of the rhizosphere, which is the area around a plant's roots. Saline soils can form due to the rise of the groundwater table, sea intrusion, or application of saline water. Accumulation of major soluble salts, including $CaCl_2$ and NaCl, results in the rise of multiple challenges. Firstly, the osmotic potential of the soil solution becomes abnormally low. The electrical conductivity (EC) of soil water can increase from 4 to 40 dS m^{-1}, and the osmotic potential can reach from -200 to -1500 kPa (Rengasamy 2010). This will impair the uptake of water and cause osmotic stress to plant roots, which directly inhibits shoot growth and crop yield of high yielding cultivars. Secondly, adsorption of higher concentrations of exchangeable sodium (referred to as 'exchangeable sodium percentage or ESP') to soil particles, characteristically defined by a higher sodium adsorption ratio (SAR) of soil solution, damages soil properties. The presence of higher residual carbonates and bicarbonate in irrigation sources allows precipitation of calcium as $CaCO_3$. This promotes excess Na^+ ions to capture clay exchange sites initially captured by Ca^{+2} or Mg^{+2} ions (Chhabra 2004). As Na^+ ions have a higher ionic size but have a lesser charge compared to Ca^{+2} ions, clay particles cannot flocculate/aggregate as they do around Ca^{+2} ions. Hence, clay particles remain dispersed, which results in the clogging of pores and hardening of soil layers. These changes slow down water drainage, ultimately resulting in waterlogging. These soils are therefore referred to as 'sodic soils.' Soils with a higher pH and clayey texture can often have salinity and sodicity in tandem. Referred to as 'saline-sodic soils,' these soils have complex salt and textural properties, causing poor root proliferation and stunted plant growth (Sparks 2003). Management of arable soil properties and irrigation is, therefore, the most accessible path to improve crop productivity in salt-affected soils.

The ideal and key practice is to use good quality water to neutralize potential osmotic stress in root zones. However, the availability of adequate quality water can be challenging in most salt-affected areas. More sustainable irrigation methods involve the application of low saline water to leach out the heavy concentration of salts in saline soils. However, sodic soils resist the process of leaching but supplementation with gypsum allows an influx of Ca^{+2} ions that can replace excess Na^+, and this way improves the physical properties of soil for effective drainage.

Wastewater application is also a good option; however, it should be actioned with caution due to the waste water's chemical and biological properties. For example, if the wastewater originates from an untreated urban resource, it could cause problems in terms of toxicity and pathological contamination. Nevertheless, more sustainable irrigation technologies can be adapted for salt-affected soils. For instance, alternate application of good and saline quality water, using drip or sprinkler irrigation, has been a widely adopted practice to leach salts from the plant's rhizospheric zones, and this method also improves the economy of irrigation and water usage (Tingwu et al. 2003; Hanson and May 2010; Sevostianova et al. 2011; Li et al. 2019).

To reduce the impact of saline water on plant roots, smarter irrigation practices can also be supplemented by adding organic acids, which can provide multiple advantages for the biochemical properties of the rhizosphere. For example, it helps promote a moderate decrease in pH in the rhizosphere, making nutrients available that are otherwise chemically fixed at a relatively higher pH, such as inorganic phosphorous; a reduction of the impact of higher EC and leach excess Na^+ ions; a better root growth; and a sustainable soil ecosystem (Jones 1998; Menezes-Blackburn et al. 2016; Adeleke et al. 2017; Macias-Benitez et al. 2020). Application of organic acids in water or rhizosphere can be achieved either through the use of microbially fermented organic substrates such as molasses or distillery waste or by using the synthetic source of organic acids such as lactic acid, citric acid, oxalic acid, or malic acid (Macias-Benitez et al. 2020). Microbially fermented molasses and organic acids are shown to significantly improve plant productivity and nutrient availability in saline-sodic, as well as in coastal saline soils (Pérez Escolar 1966; Ahmad et al. 1999; Mouhamad et al. 2017; Mtolera and Dongli 2018; Ding et al. 2020; Sun et al. 2020).

Furthermore, application of sulfuric acid, elemental sulfur, other sulfate-based amendments (ferric sulfate, calcium thiosulfate), and/or a combination of nitrogen and sulfur (N-Phuric, acid, ammonium polysulfide) has proven to be an effective transient amendment in salt-affected calcareous/lime (with > 15% of $CaCO_3$), as well as in sodic soils (Miyamoto et al. 1975; Sadiq et al. 2007; Loch and Loch 2013). Their application helps in reducing soil's pH, its high ESP, calcite content, and excess carbonates in the water. Besides the benefits of organic and inorganic forms of acids on soil chemistry, these amendments can have a dramatic impact on the rhizospheric microbial populations, which can improve rhizospheric organic acid composition. Particularly, two recent studies have shown how organic acid modulates the microbial population, which improves plant growth but also affects the presence of plant pathogens (Wu et al. 2017; Macias-Benitez et al. 2020).

Management of soil properties through physical approaches is well-proven to encourage plant root growth in salt-affected soils. For example, laser leveling of the lands makes homogenous application of water easier, allowing for a more effective leaching of salts across acreages. However, sodic soils hold a more aversive physical challenge due to hardpans formed underneath, induced by the dispersion effect of Na^+ ions on the cation exchange sites in clayey environments. To modify the sub-soil structure, these pans need to be cracked by deep plowing and tillage, combined with the addition of gypsum or sanding. These methods have the potential to promote healthy root proliferation in deeper clayey soil zones.

Utilizing organic matter can significantly support the rehabilitation process of salt-affected soils. However, this process needs to be well-integrated with crop cultivation, water management, and other agricultural practices related to soil management for effective results. In general, biodegradable solid organic matter is mostly sourced from animal waste, including poultry manure and ruminant manure from sheep, goats, and cattle. However, if crop covers in salt-affected regions are generally low, the availability of animal manures can also become limited. Other useful sources are biodegradable industrial wastes, such as sugarcane press mud and bagasse, waste from food and fruit processing industries, and municipal organic waste. On the other hand, making use of liquid organic fertilizers allows more control over the addition of nutrients and organic acids into root zones, and this method of application with water provides more flexibility in application. In terms of nutrient value, various sources of organic matter bring a range of macro- and micro-nutrient contents that exert a diverse impact on plant growth (Dotaniya et al. 2016; Park et al. 2019).

Key values in the application of organic matter in salt-affected soil are about improving soil's osmotic and physical properties in the rhizosphere. For example, organic matter improves water-holding capacity and fastens the process of aggregation in soil particles that raises soil porosity. This improves clayey, sandy textured saline, as well as saline-sodic soils. Furthermore, organic matter reduces pH, improves microbial activity, and helps leach Na^+ ions, thereby lowering EC and ESP up to 87 and 71%, respectively (Tejada et al. 2006; Wu et al. 2013; Wang et al. 2014; Liu et al. 2017; Seleiman and Kheir 2018; Ding et al. 2020; Wichern et al. 2020). Prominent facultative anaerobic microbial species, also known as effective or beneficial microorganisms, such as lactic acid bacteria (*Lactobacillus* sp.), yeast (Saccharomyces cerevisiae), and actinomycetes, can perform fermentation of the organic matter and produce organic acids and bioactive metabolites. This helps maximize the impact of applying organic matter to buffer salt stress in the rhizosphere and benefits crop growth and yield directly (Hussain et al. 1999; Yamada and Xu 2001; Khaliq et al. 2006; Lakhdar et al. 2009; Sidhu et al. 2009; Iriti et al. 2019).

Regions with high temperature and little rainfall are prone to the degradation of organic matter, and, therefore, the usage of an 'open-fermenter' system has shown an advantage in the reclamation of salt-affected soils. The 'open-fermenter' system allows mixing of the irrigation water with the slurry of fermented organic manures. With each field application of water, beneficial microbes, as well as fermented slurry, are distributed into the field. This has been shown to provide multiple benefits besides the flexibility of the application of organic matter in a canal-based irrigation system. For example, the addition of organic slurry has shown to reduce the adverse effects of saline water, recharge the organic matter in the field by microbial-led fermentation of green crop residues, help lower the Carbon: Nitrogen (C: N) ratio, and improve the water-holding capacity in sandy saline soils (Hussain 2000; Hussain et al. 2004; Naveed et al. 2015).

Microbial-induced salt tolerance has further shown the potential of certain bacterial species to provide resilience against salt stress in plants. Generally referred to as 'plant growth-promoting rhizobacteria,' several Gram-positive and Gram-negative bacteria, as well as fungal species that inhabit the rhizosphere, carry an enzyme known as 1-aminocyclopropane-1-carboxylate deaminase (ACCD) which degrades ACC in root exudates (Singh et al. 2015). ACC is the precursor of the plant stress hormone ethylene. Initially found in *Pseudomonas* sp., ACCD metabolizes ACC within bacterial cells, which results in a concentration gradient in the rhizosphere, allowing exclusion of more ACC from the roots, thereby reducing the levels of ACC within plants and consequently resulting in reduced biosynthesis of the stress hormone ethylene in plant roots (Glick et al. 1998). This bacterial trait has been shown to promote root biomass and induce salt tolerance and plant growth (Glick 2014; Misra et al. 2017; Maxton et al. 2018; Sarkar et al. 2018; Chandra et al. 2019); however, microbial metabolites may also be involved in improving crop physiology.

A collection of exploratory studies has utilized genomic tools to enlist several microbial species found in the rhizosphere of salt-tolerant plants (halophytes) (Ruppel et al. 2013). These plants have adapted to environments including deserts, seas, salt lakes, and salt mines. Microbes inhabiting these plants are being studied and utilized in promoting salt tolerance in non-halophyte plants (Shivakumar and Bhaktavatchalu, 2017; Kearl et al. 2019; ALKahtani et al. 2020a; Benidire et al. 2020; Ilyas et al. 2020; Naamala and Smith 2020; Shultana et al. 2020). The halophyte microbiome can survive in extreme salt concentrations and alkaline pH, due to their genetic traits associated with cell wall strengthening, excluding salts from the cellular environment and accumulating organic osmolytes. These microbes can perform different functions which may include nitrogen fixation, which benefits plants directly, and release exopolysaccharides, which increase water-holding capacity, shield from excess salts, and create micro-niches that help the rhizosphere being colonized by other beneficial microbes. Halophyte microbes are also found to release acidic metabolites, which promote the solubilization of minerals, including phosphates and micronutrients.

Furthermore, these microbes can modulate plant hormone levels as in the ACCD activity described above and also modify the growth-promoting hormones auxins and gibberellins, and bioactive compounds, including polyamines and other secondary metabolites, as well as amino acids (Sgroy et al. 2009; Khan and Bano 2019; Khan et al. 2020). Interestingly, microbes not only colonize the salty rhizosphere but also the endophytic space. Endophytes include prokaryotic and eukaryotic microbes that perform symbiotic colonization of plant tissues, specifically in the apoplastic space of leaves, intracellular spaces among root cells, and phloem or xylem tissues (Lata et al. 2019). These microbes provide numerous benefits for plants, including nutrients and active metabolites which strengthen plants against salt, drought, nutrient, and biotic stresses. For example, arbuscular mycorrhizal fungi are well-studied endophytic microbial species that produce antioxidants and osmoprotectants while colonizing plant roots, which neutralizes reactive oxygen species (ROS) accumulated in plants during salt stress and promotes ionic balance. Similarly, endophytic microbes discovered in leaf tissues of the desert and coastal plants contribute toward abiotic stress resilience (Arora et al. 2014; Eid et al. 2019; Fouda et al. 2019; ALKahtani et al. 2020b).

3 Coding for Salt Tolerance and Desert's Genetics

Beyond external approaches that mitigate salt tolerance in plants, taking advantage of plant's genetics will help transcend the ultimate problem of salt stress. Plants naturally exhibit various kinds of mechanisms that alleviate salt-driven hyperosmotic stress. Accumulation of salts in the plant's cellular environment is followed by a burst of intracellular ROS, activation of apoptosis, and, consequently, cell death in salt-sensitive plants (glycophytes). Salt tolerance in plants relies on plants employing mechanisms and involves exclusion of Na^+ ions, ion homeostasis, compartmentalization of salts in the vacuole, and biosynthesis of osmoprotectants, as well as generation of metabolites, antioxidant compounds, and solutes. All these mechanisms promote ionic balance and perform effective detoxification of ROS.

Natural variation in salt stress tolerance has been observed in the plant kingdom and in many plant species, like cereals, vegetables, fruit, and fodder crop; it is known whether they confer a lower or a higher threshold of resistance to saline stress (listed in Table 1a). They can be used as an alternative in a conventional cropping system and, therefore, have a central position in the saline agricultural system and livelihood security (Banyal et al. 2019). Utilizing these alternative crops can be further partnered with employing agroforestry, where trees from various species (listed in Table 1a) show naturally better salt tolerance and a promise in the rehabilitation of salty soils.

Programs for breeding for salt tolerance in primary agricultural monocots (wheatgrasses, barley, and wheat) have been in progress since the 1950s (Norlyn 1980). Access to the wild germplasm of main cereals and vegetable crops, that shows salt tolerance, allows the development of breeding populations that segregate for yield and salt tolerance. Unlike a trait such as sex phenotype in plants, which is controlled by one or two genes, natural variation is present for salt tolerance in most cultivated plant species where several genes seem to contribute to the level of salt tolerance. Being a non-mendelian trait, salt fitness has a normal distribution among breeding populations of cereals and other crops. Hence, a super-salt-tolerant cereal cultivar that has a higher threshold for tolerating salinity and a perfect introgression of other traits such as yield remains moderately achievable with little success.

With the advent of new genotyping technologies, genetic polymorphisms among accessions and breeding populations of cereals and other crops could be scored at a much higher density and with significant statistical confidence (Scheben et al. 2018). This allowed the construction of ultra-dense genetic maps and genome-wide association studies have become easier to conduct, which now helps explore genotype x environmental (GxE) interactions (Beres et al. 2020). Advances in genomics have made it possible to expand genetic studies of agricultural species that are complex at the genome level and exhibit higher ploidy levels (Dufresne et al. 2014; Bourke et al. 2018; Kyriakidou et al. 2018), such as bread wheat (*Triticum aestivum*), which is a hexaploid and carries three copies of different sub-genomes (i.e., six copies of each chromosome), compared to the cultivated Asian rice (*Oryza sativa*) which is a diploid (i.e., with two copies of each chromosome).

Population genetics has helped to identify several quantitative trait loci (QTLs) and genetic markers associated with salt tolerance in cereals and other crops (Flowers et al. 1997; Ashraf and Foolad 2013; Fita et al. 2015; Hanin et al. 2016; Hoang et al. 2016; Ismail and Horie 2017; Patishtan et al. 2018; Xie et al. 2019; Chaurasia et al. 2020; Chen et al. 2020). With the progressive advance in developing reference, whole genome sequences of cereals (Paterson et al. 2005; Varshney et al. 2006; Guan et al. 2020) and candidate genes underlying these genetic hotspots have been identified

Table 1 Salt-tolerant crops

Common name	Scientific name
(a) Common agricultural crops and trees which show moderate to high salt tolerance	
Alfalfa	*Medicago sativa*
Barley	*Hordeum vulgare*
Cabbage	*Brassica oleracea*
Chilies	*Capsicum annuum*
Cluster bean	*Cyamopsis tetragonoloba*
Date-palm	*Phoenix dactylifera*
Eucalyptus	*Eucalyptus camaldulensis*
Farash	*Tamarix articulate*
Guava	*Psidium guajava*
Jambolana	*Syzygium cumini*
Kikar	*Acacia nilotica*
Okra	*Abelmoschus esculentus*
Onion	*Allium cepa*
Pearl millet	*Cenchrus americanus*
Phalsa	*Grewia asiatica*
Pomegranate	*Punica granatum*
Sorghum	*Sorghum bicolor*
Spinach	*Spinacia oleracea*
Sudangrass	*Sorghum sudanense*
Sugar beet	*Beta vulgaris*
(b) Halophytes	
Alkali/rosin weed	*Cressa cretica*
Beaded samphire/glasswort	*Salicornia* and *Sarcocornia* sp.
Buck's-horn plantain	*Plantago coronopus*
Camelthorn	*Alhagi maurorum*
Glaucous glasswort	*Arthrocnemum macrostachyum*
Golden samphire	*Inula crithmoides*
Ijlah	*Halopyrum mucronatum*
Palmer saltgrass	*Distichlis palmeri*
Purslane	*Portulaca oleracea*
Quinoa, goosefoot	*Chenopodium quinoa,*
Saltwort	*Batis maritima*
Saxaul	*Haloxylon stocksii*
Sea aster	*Aster tripolium*
Shrubby seablite	*Suaeda fruticosa*
Salt bush	*Atriplex halimus*

by using short-read, long-read, or single DNA molecule sequencing technologies, which provide insights into the genic network governing tolerance and adaptation to salt stress in primary agriculture crops. Most of these genes are also found to be differentially expressed in response to salt stress within 3–24 h in response to the accumulation of higher amounts of Na^+ and Cl^- ions in the cytosolic environment in salt-tolerant plants. These genes encode (Kreps et al. 2002; Amirbakhtiar et al. 2019; Liu et al. 2019; Han et al. 2020):

- enzymes which reduce oxidative stress, for example, glutathione reductase, glutathione S-transferase, peroxidase, glutaredoxins, and cytochrome P450;
- transcription factors, belonging to families of bHLHs, bZIPs, AP2/ERF, ZFPs, NACs, WRKYs, and HD-ZIP;
- plasma and tonoplast membrane-based Na^+/H antiporters and Na^+/H^+ exchangers (NHX1 and NHX2), respectively (also part of salt overly sensitive (SOS) pathway), which dump sodium out of cells or perform its compartmentalization in the vacuole;
- Vacuolar H^+-pyrophosphatase (VP) which acts as H^+ pump that can mediate sodium compartmentalization;
- calcium-transporter ATPases which contribute in ion homeostasis;
- $Na^+/Ca_2{}^+$ exchanger proteins which are localized on plasma membrane and carry homeostasis for Ca^{+2} and Na^+ ions;
- aquaporins, which control ion and water transport;
- hydrophilic, glycine-rich late-embryogenesis-abundant (LEA) proteins/dehydrins, which act as chaperones to other proteins, bind to metal ions, may also scavenge ROS, and stabilize membrane structure;
- proteins involved in histone modification and methylation and maintaining chromatin state;
- beta-glucosidase, shikimate *O*-hydroxycinnamoyl transferases, and other enzymes involved in biosynthesis of secondary metabolites in the phenyl-propanoid pathway, such as flavanols and phenols, which act as ROS scavenger, lignification, and terpenoids;
- proteins involved in carbohydrate metabolism, especially cell wall invertase and sucrose synthase, as sugar molecules maintain osmotic balance during salt stress; and
- proteins involved in signaling of plant hormones, including ethylene and abscisic acid.

There are many more genes identified in various salt-tolerant crops that are upregulated in salt stress and have functions involved in ion transport, amino acid metabolism, phosphorylation, splicing machinery, redox sensors, membrane potential, photosynthesis, signaling, and ATP biosynthesis (Zhang et al. 2016; Razzaque et al. 2019). Furthermore, expression of these genes is maintained for a longer period in salt-tolerant vs. salt-sensitive plants. Interestingly, genes associated with salt tolerance in roots are found to be functionally different compared to those that are associated with this trait in plant leaves or shoot tissues, and this suggests tissue-specific regulation of salt tolerance in plants. Most of these genes appear to be involved in drought stress response too.

The breeding of salt-resistant cultivars in cereals has led to develop the more tolerant high-Na^+ bread wheat germplasm MW#293, which has better fitness in saline and sodic soil conditions and higher grain yield compared to other bread wheat cultivars (Genc et al. 2019). Other candidate genes identified through QTL mapping and introgressed into commercial cultivars are *KNA*1 and *NAX*2, which are involved in the efflux and transport of sodium, respectively (Byrt et al. 2007; Munns et al. 2012). Similarly, wild germplasm of rice has been explored to find the best salt-tolerant lines carrying a novel 'Saltol' QTL and other QTLs, that will be used in the development of novel salt-resistant cultivars in the future (Quan et al. 2018; Solis et al. 2020).

Candidate mechanisms for improving salt tolerance in glycophytes follow these paths: sensing of ionic imbalance and transport of Na^+ ions across the membrane into vacuoles, efflux from roots and leaf tissues as well as xylem-specific unloading and loading of Na^+ ions; homeostasis of cytosolic Ca^{+2}, K^+, and Cl^- ions and efflux of K^+ ions; activation of antioxidant defense plethora to timely scavenge ROS accumulation; and accumulation of osmolytes and osmoprotectants including glycine, betaine, proline, and sugars.

A rise in salinity and high temperatures, however, brings a significant challenge to grow these relatively salt-tolerant crop species in extremely harsh conditions. In this scenario, utilizing halophytes provides a significant opportunity to understand the genetics which stores key information on how plants can survive and grow on land with extreme salinity (Glenn et al. 1999). Halophytes can tolerate 70–300 mM of NaCl in the soil solution, which is still well below that of seawater at 550–600 mM (Millero et al. 2008). Around 2000 halophytic species are listed in the eHALOPH Halophyte Database (Santos et al. 2016), mostly originating from the Mediterranean Basin. Most halophytes are rich in healthy bioactive compounds as well as proteins, vitamins, antioxidants, and minerals, which have a range of medicinal properties. However, they are not highly edible, and hence, breeding programs are targeting the development of elite edible halophyte cultivars for quality food production. Prominent halophytes carry a great potential for medicinal and food production in non-habitable salt-affected soils and include vegetables, grain crops, oilseeds, and fodder (listed in Table 1b).

Quinoa (*Chenopodium quinoa*) is a remarkable example of an extremely salt and drought-tolerant plant species, producing amino acid, vitamin, mineral, and fiber-enriched seeds. The plant can also adapt to other abiotic stresses like temperature variations, ranging from −4 to 38 °C, as well as to high humidity. The quinoa breeding program is one perfect example of extreme saline agriculture and shows a way for improving grain yield and reducing saponin levels (Fita et al. 2015). Another great exemplar is the planting of thousands of hectares of land in the Mediterranean Basin with *Atriplex* spp., which provide high-nitrogen forage for ruminants (Houérou

1994). The usage of salt-tolerant fodder crops in Egypt has been shown to improve milk production and reduce feeding costs, thereby directly supporting the livelihood in marginal lands (El Shaer and Al Dakheel 2016).

Halophytes are superbly efficient in both excluding salt and retaining higher levels of salts in plant tissues. This ability is dependent upon the machinery of ion channels, transporters, excluders and exchangers, ROS scavengers, and osmolyte generators; so, the use of these mechanisms is also tried in breeding salt tolerance in glycophytes. However, in halophytes, this machinery is more evolved with changes at the gene transcriptional levels in various tissues, genetic polymorphism which accounts for subtle yet impactful changes in protein affinities, post-translational modifications, and novel regulation and integration of ion transport pathways in various tissues (Assaha et al. 2017). For example, the expression of the *SOS*1 antiporter gene, which excludes Na^+ ions to rhizosphere from the root epidermal cells, is relatively high in both roots and shoots in a halophyte *Thellungiella salsuginea* compared to the glycophyte model plant *Arabidopsis thaliana* (Oh et al. 2009). RNA interference (RNAi)-mediated suppression of *SOS*1 antiporter gene expression in *T. salsuginea* is shown to turn this halophyte into a salt-sensitive plant, whereas expression of the *T. salsuginea*'s *SOS*1 gene in *A. thaliana* makes it salt tolerant. *SOS*1 is also involved in the xylem loading of Na^+ ions, thereby adjusting the shoot Na^+/K^+ ratio. Its expression is highly enhanced in the roots of the salt-accumulating halophyte *Salicornia spp.*, to direct more Na^+ ions into the shoot for accumulation. This would be lethal in general for a glycophyte though. Reduced accumulation of sodium in leaves is further maintained by *HKT* genes, by transferring sodium from the xylem into xylem parenchyma cells. A higher expression of these genes is associated with salt tolerance in a tomato cultivar, as well as in other *Solanaceous* species and rice cultivars. Transfer of sodium in vacuoles is crucial to avoid sodium toxicity in the cytosol, and tonoplast-localized fast vacuolar (FV) and slow vacuolar (SV) channels can disturb this process by excluding vacuolar potassium ions, besides leaking Na^+ ions, back into the cytosol. Halophyte quinoa is found to have reduced activity and closure of FV and SV channels, which helps in its ability in regulating salt accumulation in vacuoles (Bonales-Alatorre et al. 2013).

The genes which regulate salt tolerance in halophytes are targeted for genetic engineering by genetic modifications (GM) for inducing salt tolerance in glycophytes (Fita et al. 2015). However, traditional genetically modified crops are not accepted in all consumer markets worldwide, due to the transfer of foreign DNA into the cultivar derived from other species or another cultivar of the same species. Recent advances in GM techniques can generate mutations by introducing specific double-strand breaks (DSBs) at the target sites of genes regulating salt tolerance. This can be achieved by CRISPR (clustered regularly interspaced short palindromic repeats/Cas9) gene-editing technology, which would be revolutionary in developing GMO-free salt-tolerant varieties of agricultural glycophytes (Farhat et al. 2019). Indeed, a few studies have already shown the usage of CRISPR/Cas9 technology in generating non-GM salt-tolerant rice varieties (Zhang et al. 2019; Santosh Kumar et al. 2020).

4 Advances in Urban Agriculture

Future predictions based on global climate change suggest that arid and semi-arid areas will experience huge water shortages, which will ultimately cause more saline soils. Salinity is one of the major abiotic factors limiting global agricultural productivity, rendering an estimated one-third of the world's irrigated land unsuitable for crops (Frommer et al. 1999). Given the predicted rise in world population, the supply of fresh water required for agricultural use will become limited, and utilizing seawater will become the best option. Besides, other abiotic stress factors associated with climate change and industrialization, such as high temperature, pest and disease infestations, and metal toxicity, put significant pressure on breeding programs for various crops, to integrate traits that help plants thrive in a changing environment. Therefore, it is important to consider different options in farming practices and adopt cropping systems that have the potential to provide sustainable food sources. Indoor farming—or 'urban agriculture'—offers an alternative self-sufficient system to grow all types of crops in a fixed environment.

Climate change and a rapidly increasing population (Fedoroff 2015; Haddad et al. 2016) are among the key reasons to push for the concept of indoor farming systems, which offer a huge potential to become a new sustainable cropping system (Despommier 2019). Production of crops in controlled environments is feasible, sustainable, and nature friendly (Despommier, 2010; Kumar et al. 2020). Moreover, modern advancements in lighting, ventilation, robotics, and irrigation techniques are enabling farmers to grow food indoors, on previously unused spaces such as rooftops, garages, and deserts. Compared to flat indoor farming, vertical farming can even further improve the usage of space. Indoor farms utilize soilless growing media, such as hydroponics, aquaponics, and aeroponics, and renewable energy resources including solar power, wind energy, reusable city's treated wastewater, and desalinated water. Desalinization of water can be achieved through different technologies, including reverse osmosis or energy-dependent distillation of water that can employ a combination of energy resources (Chian et al. 2007; Davenport et al. 2018; Gude 2018; Juneseok Lee 2019). Graphene-based new technology for the desalinization of water has the potential to reduce the cost of desalinization and support urban agriculture in the future (Boretti et al. 2018). Furthermore, research has been accelerating on quenching water from the air to support water availability in urban and desert agriculture. Fog harvesting, dew water harvesting, and condensation technology are a few emerging methods in water harvesting technology (Jarimi et al. 2020). The availability of clean and salt-free water will be pivotal in driving sustainable food production in both urban agriculture and salt-affected regions.

Although the initial cost for constructing indoor farms is high, indoor farming enhances land-use efficiency, provides food year-round, allows sustainable urban food production, protects vegetable and fruit production systems from extreme climate change, and, very importantly, saves water (Kumar et al. 2020). Many countries such as China, Japan, UAE, and Israel have already taken the lead in growing various crop plants under these new flat and vertical indoor growing systems.

Besides providing food production throughout the year, indoor farming reduces the risk of losing crops due to environmental threats such as high temperature, salt stress, drought, and new pathogens and pests (Benke and Tomkins 2017). Agriculture in indoor systems in deserts located nearby the sea could potentially make use of seawater for irrigation. Here, the greatest challenge for future farmers is to adopt a new set of farming practices, taking into account the preference for salinity-resistant species that perform better in indoor farms. When plants are exposed to a moderate amount of salt, they produce many bioactive constituents including sugars, carbohydrates, lipids, polyphenolics, and antioxidants (Cuartero et al. 2006; Rouphael et al. 2012). Fruits and vegetables grown under salt conditions are a good source of health-promoting phytochemicals. Developing new breeding techniques, such as rapid growth and growth in low light environments, and using genetic traits by active manipulation of plant stature will open opportunities for future expansions.

Moreover, breeders have selected crop traits that are specific for growing in a wide spectrum of growing conditions. This has left modern agriculture depending on a small number of cultivars for major crop production (Dwivedi et al. 2017). Indoor farming may provide solutions for enhancing crop adaptation to abiotic stress, as well as being a new source of healthy and nutritious food. There is a dire need to investigate, understand, and initiate the research to breed the crops needed for urban farming. To date, very few crops such as lettuce, tomatoes, and strawberries are shown to perform to their full potential in indoor farming systems (Cox 2016). The possibility to grow other varieties by indoor farming warrants investigation. Many recent studies suggest that crops such as grains, grapes, berry fruits, soy, and tree fruit are promising candidates for growth in indoor farms. Similarly, indoor farming has a huge prospective for growing pharmaceutical crops such as cannabis, where cultivation needs to be contained and monitored (Chandra et al. 2017). Current breeding and genome modification methods deliver a robust approach for creating new cultivars suitable for indoor environments. For example, the CRISPR–Cas9 genome-editing tool has been employed to create an early high yielding tomato plant, appropriate for urban agriculture (Kwon et al. 2020). Similarly, cross-breeding of commercial crops with their wild-type relative can explore the traits mandatory for traditional farming systems but which can be embraced in indoor farming.

5 Conclusion

The plant's fight against salinization starts at the rhizospheric interface, and it is becoming clear that with the onset of unprecedented climate change in recent times, agricultural lands are continuously becoming more saline and unfit for conventional farming practices. More than ever, we are aware of the need for different approaches in agriculture that can enable and improve crop growth on marginal lands that have not been used by conventional farming before. It is therefore imperative to combine these approaches and establish integrative model systems for crop production in salty regions in various countries. These model systems can be developed under national research programs, and data from the usage of methodologies and technologies, along with their affordability and impact, can be used to predict and improve the ability of various crops and trees in salt-affected soils. These steps can prepare us for a sustainable food production system in saline regions.

The security of our agriculture and food production relies on a combination of biosaline agriculture, coupled with genetic modification of key genes, in order to turn desired plant species into salt-resistant or even salt-loving cultivars. A key element to reach this goal requires the funding of research programs for advancing integrative genomics, genetics, and breeding of glycophytes and halophytes, to create new salt-tolerant grain, vegetable, and fruit cultivars and thus ensure basic and quality food production in countries most affected by salinization. Combined with the emerging shift toward indoor agriculture, which acts as a parallel stream of evolution in modern agriculture, this will help secure food production for a growing global population in a self-sustainable model.

References

Adeleke R, Nwangburuka C, Oboirien B (2017) Origins, roles and fate of organic acids in soils: a review. S Afr J Bot 108:393–406

Ahmad S, Aslam M, Zeb J, Hussian T, Zia M (1999) EM bio-generator for amending sodic groundwater

ALKahtani MDF, Attia KA, Hafez YM, Khan N, Eid AM, Ali MAM, Abdelaal KAA (2020a) Chlorophyll fluorescence parameters and antioxidant defense system can display salt tolerance of salt acclimated sweet pepper plants treated with chitosan and plant growth promoting rhizobacteria. Agronomy 10:1180

ALKahtani MDF, Fouda A, Attia KA, Al-Otaibi F, Eid AM, Ewais EE-D, Hijri M, St-Arnaud M, Hassan SE-D, Khan N, Hafez YM, Abdelaal KAA (2020b) Isolation and characterization of plant growth promoting endophytic bacteria from desert plants and their application as bioinoculants for sustainable agriculture. Agronomy 10:1325

Amirbakhtiar N, Ismaili A, Ghaffari MR, Nazarian Firouzabadi F, Shobbar Z-S (2019) Transcriptome response of roots to salt stress in a salinity-tolerant bread wheat cultivar. PLOS ONE 14:e0213305

Arora S, Patel PN, Vanza MJ, Rao G (2014) Isolation and characterization of endophytic bacteria colonizing halophyte and other salt tolerant plant species from coastal Gujarat. Afr J Microbiol Res 8:1779–1788

Ashraf M, Foolad MR (2013) Crop breeding for salt tolerance in the era of molecular markers and marker-assisted selection. Plant Breed 132:10–20

Assaha DVM, Ueda A, Saneoka H, Al-Yahyai R, Yaish MW (2017) The role of Na+ and K+ transporters in salt stress adaptation in glycophytes. Front Physiol 8

Banyal R, Sanwal SK, Sharma PC, Yadav RK, Dagar JC (2019) Fruit and vegetable-based saline agricultural systems for nutritional and livelihood security. In: Dagar JC, Yadav RK, Sharma PC (eds) Research developments in saline agriculture. Springer, Singapore, pp 729–751

Benidire L, El Khalloufi F, Oufdou K, Barakat M, Tulumello J, Ortet P, Heulin T, Achouak W (2020) Phytobeneficial bacteria improve saline stress tolerance in Vicia faba and modulate microbial interaction network. Sci Total Environ 729:139020

Benke K, Tomkins B (2017) Future food-production systems: vertical farming and controlled-environment agriculture. Sustain Sci Pract Policy 13:13–26

Beres BL, Hatfield JL, Kirkegaard JA, Eigenbrode SD, Pan WL, Lollato RP, Hunt JR, Strydhorst S, Porker K, Lyon D, Ransom J, Wiersma J (2020) Toward a better understanding of genotype × environment × management interactions—a global wheat initiative agronomic research strategy. Front Plant Sci 11

Bonales-Alatorre E, Shabala S, Chen Z-H, Pottosin I (2013) Reduced tonoplast fast-activating and slow-activating channel activity is essential for conferring salinity tolerance in a facultative halophyte, Quinoa. Plant Physiol 162:940–952

Boretti A, Al-Zubaidy S, Vaclavikova M, Al-Abri M, Castelletto S, Mikhalovsky S (2018) Outlook for graphene-based desalination membranes. npj Clean Water 1:5

Bourke PM, van Geest G, Voorrips RE, Jansen J, Kranenburg T, Shahin A, Visser RGF, Arens P, Smulders MJM, Maliepaard C (2018) polymapR—linkage analysis and genetic map construction from F1 populations of outcrossing polyploids. Bioinformatics 34:3496–3502

Byrt CS, Platten JD, Spielmeyer W, James RA, Lagudah ES, Dennis ES, Tester M, Munns R (2007) HKT1;5-like cation transporters linked to Na+ exclusion loci in wheat, Nax2 and Kna1. Plant Physiol 143:1918–1928

Chandra S, Lata H, ElSohly MA (2017) Cannabis sativa L.-botany and biotechnology. Springer, Berlin

Chandra D, Srivastava R, Gupta VVSR, Franco CMM, Sharma AK (2019) Evaluation of ACC-deaminase-producing rhizobacteria to alleviate water-stress impacts in wheat (Triticum aestivum L.) plants. Can J Microbiol 65:387–403

Chaurasia S, Singh AK, Songachan LS, Sharma AD, Bhardwaj R, Singh K (2020) Multi-locus genome-wide association studies reveal novel genomic regions associated with vegetative stage salt tolerance in bread wheat (Triticum aestivum L.). Genomics 112:4608–4621

Chen C, Norton GJ, Price AH (2020) Genome-wide association mapping for salt tolerance of rice seedlings grown in hydroponic and soil systems using the Bengal and Assam Aus panel. Front Plant Sci 11

Chhabra R (2004) Classification of salt-affected soils. Arid Land Res Manag 19:61–79

Chian ESK, Chen JP, Sheng P-X, Ting Y-P, Wang LK (2007) Reverse osmosis technology for desalination. In: Wang LK, Hung Y-T, Shammas NK (eds) Advanced physicochemical treatment technologies. Humana Press, Totowa, NJ, pp 329–366

Cox S (2016) Enough with the vertical farming fantasies: there are still too many unanswered questions about the trendy practice. Salon, Feb 17

Cuartero J, Bolarin M, Asins M, Moreno V (2006) Increasing salt tolerance in the tomato. J Exp Bot 57:1045–1058

Davenport DM, Deshmukh A, Werber JR, Elimelech M (2018) High-pressure reverse osmosis for energy-efficient hypersaline brine desalination: current status, design considerations, and research needs. Environ Sci Technol Lett 5:467–475

Despommier D (2010) The vertical farm: feeding the world in the 21st century. Macmillan, London

Despommier D (2019) Vertical farms, building a viable indoor farming model for cities. Field actions science reports. J Field Actions 68–73

Ding Z, Kheir AMS, Ali MGM, Ali OAM, Abdelaal AIN, Lin XE, Zhou Z, Wang B, Liu B, He Z (2020) The integrated effect of salinity, organic amendments, phosphorus fertilizers, and deficit irrigation on soil properties, phosphorus fractionation and wheat productivity. Sci Rep 10:2736

Dotaniya ML, Datta SC, Biswas DR, Dotaniya CK, Meena BL, Rajendiran S, Regar KL, Lata M (2016) Use of sugarcane industrial by-products for improving sugarcane productivity and soil health. Int J Recycl Org Waste Agric 5:185–194

Dufresne F, Stift M, Vergilino R, Mable BK (2014) Recent progress and challenges in population genetics of polyploid organisms: an overview of current state-of-the-art molecular and statistical tools. Mol Ecol 23:40–69

Dwivedi SL, Scheben A, Edwards D, Spillane C, Ortiz R (2017) Assessing and exploiting functional diversity in germplasm pools to enhance abiotic stress adaptation and yield in cereals and food legumes. Front Plant Sci 8:1461

Eid AM, Salim SS, Hassan SE-D, Ismail MA, Fouda A (2019) Role of endophytes in plant health and abiotic stress management. In: Microbiome in plant health and disease. Springer, Berlin, pp 119–144

El Shaer HM, Al Dakheel AJ (2016) 11-sustainable diversity of salt-tolerant fodder crop–livestock production system through utilization of saline natural resources: Egypt case study. In: Khan MA, Ozturk M, Gul B, Ahmed MZ (eds) Halophytes for food security in dry lands. Academic Press, San Diego, pp 177–195

Farhat S, Jain N, Singh N, Sreevathsa R, Dash PK, Rai R, Yadav S, Kumar P, Sarkar AK, Jain A, Singh NK, Rai V (2019) CRISPR-Cas9 directed genome engineering for enhancing salt stress tolerance in rice. Semin Cell Dev Biol 96:91–99

Fedoroff NV (2015) Food in a future of 10 billion. Agric Food Secur 4:1–10

Fita A, Rodríguez-Burruezo A, Boscaiu M, Prohens J, Vicente O (2015) Breeding and domesticating crops adapted to drought and salinity: a new paradigm for increasing food production. Front Plant Sci 6

Flowers TJ, Garcia A, Koyama M, Yeo AR (1997) Breeding for salt tolerance in crop plants—the role of molecular biology. Acta Physiol Plant 19:427–433

Fouda A, Hassan S, Eid AM, El-Din Ewais E (2019) The interaction between plants and bacterial endophytes under salinity stress. In: Endophytes and secondary metabolites. Springer, Cham, pp 1–18

Frommer WB, Ludewig U, Rentsch D (1999) Taking transgenic plants with a pinch of salt. Science 285:1222–1223

Genc Y, Taylor J, Lyons G, Li Y, Cheong J, Appelbee M, Oldach K, Sutton T (2019) Bread wheat with high salinity and sodicity tolerance. Front Plant Sci 10:1280–1280

Glenn EP, Brown JJ, Blumwald E (1999) Salt tolerance and crop potential of halophytes. Crit Rev Plant Sci 18:227–255

Glick BR (2014) Bacteria with ACC deaminase can promote plant growth and help to feed the world. Microbiol Res 169:30–39

Glick BR, Penrose DM, Li J (1998) A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria. J Theor Biol 190:63–68

Guan J, Garcia DF, Zhou Y, Appels R, Li A, Mao L (2020) The battle to sequence the bread wheat genome: a tale of the three kingdoms. Genomics Proteomics Bioinform 18(3):221–229

Gude VG (2018) Chapter 10—energy storage for desalination. In: Gude VG (ed) Renewable energy powered desalination handbook. Butterworth-Heinemann, UK, pp 377–414

Haddad L, Hawkes C, Webb P, Thomas S, Beddington J, Waage J, Flynn D (2016) A new global research agenda for food. Nature 540:30–32

Han B, Xu W, Ahmed N, Yu A, Wang Z, Liu A (2020) Changes and associations of genomic transcription and histone methylation with salt stress in castor bean. Plant Cell Physiol 61:1120–1133

Hanin M, Ebel C, Ngom M, Laplaze L, Masmoudi K (2016) New insights on plant salt tolerance mechanisms and their potential use for breeding. Front Plant Sci 7:1787–1787

Hanson B, May D (2010) Salinity control with drip irrigation. In: 2010 Pittsburgh, Pennsylvania, June 20–June 23, 2010. ASABE, St. Joseph, MI

Hoang TML, Tran TN, Nguyen TKT, Williams B, Wurm P, Bellairs S, Mundree S (2016) Improvement of salinity stress tolerance in rice: challenges and opportunities. Agronomy 6:54

Houérou HNL (1994) Forage halophytes and salt-tolerant fodder crops in the Mediterranean Basin. In: Squires VR, Ayoub AT (eds) Halophytes as a resource for livestock and for rehabilitation of degraded lands. Springer Netherlands, Dordrecht, pp 123–137

Hussain T (2000) Technology of beneficial microorganisms. BM-Technology

Hussain T, Javaid T, Parr JF, Jilani G, Haq MA (1999) Rice and wheat production in Pakistan with effective microorganisms. Am J Altern Agric 14:30–36

Hussain T, Anwar-ul-Haq M, Tahir J (2004) Use of BM-technology in integrated nutrient management for rice–wheat and cotton production. Research Institute of Organic Agriculture, Yangpyung, pp 304–314

Ilyas N, Mazhar R, Yasmin H, Khan W, Iqbal S, Enshasy HE, Dailin DJ (2020) Rhizobacteria isolated from saline soil induce systemic tolerance in wheat (Triticum aestivum L.) against salinity stress. Agronomy 10:989

Iriti M, Scarafoni A, Pierce S, Castorina G, Vitalini S (2019) Soil application of effective microorganisms (EM) maintains leaf photosynthetic efficiency, increases seed yield and quality traits of bean (Phaseolus vulgaris L.) plants grown on different substrates. Int J Mol Sci 20:2327

Ismail AM, Horie T (2017) Genomics, physiology, and molecular breeding approaches for improving salt tolerance. Annu Rev Plant Biol 68:405–434

Jarimi H, Powell R, Riffat S (2020) Review of sustainable methods for atmospheric water harvesting. Int J Low-Carbon Technol 15:253–276

Jones DL (1998) Organic acids in the rhizosphere—a critical review. Plant Soil 205:25–44

Juneseok Lee TY (2019) Desalination: opportunities and challenges. https://www.waterworld.com/

Kearl J, McNary C, Lowman JS, Mei C, Aanderud ZT, Smith ST, West J, Colton E, Hamson M, Nielsen BL (2019) Salt-tolerant halophyte rhizosphere bacteria stimulate growth of alfalfa in salty soil. Front Microbiol 10

Khaliq A, Abbasi MK, Hussain T (2006) Effects of integrated use of organic and inorganic nutrient sources with effective microorganisms (EM) on seed cotton yield in Pakistan. Biores Technol 97:967–972

Khan N, Bano A (2019) Exopolysaccharide producing rhizobacteria and their impact on growth and drought tolerance of wheat grown under rainfed conditions. PLoS ONE 14:e0222302

Khan N, Ali S, Tariq H, Latif S, Yasmin H, Mehmood A, Shahid MA (2020) Water conservation and plant survival strategies of rhizobacteria under drought stress. Agronomy 10:1683

Kreps JA, Wu Y, Chang H-S, Zhu T, Wang X, Harper JF (2002) Transcriptome changes for arabidopsis in response to salt, osmotic, and cold stress. Plant Physiol 130:2129–2141

Kumar A, Shukla S, Dixit P, Tsewang T, Kumar K (2020) Vertical farming promising cultivation for horticultural crops. Int J Curr Microbiol App Sci 9:2491–2494

Kwon C-T, Heo J, Lemmon ZH, Capua Y, Hutton SF, Van Eck J, Park SJ, Lippman ZB (2020) Rapid customization of Solanaceae fruit crops for urban agriculture. Nat Biotechnol 38:182–188

Kyriakidou M, Tai HH, Anglin NL, Ellis D, Strömvik MV (2018) Current strategies of polyploid plant genome sequence assembly. Front Plant Sci 9

Lakhdar A, Rabhi M, Ghnaya T, Montemurro F, Jedidi N, Abdelly C (2009) Effectiveness of compost use in salt-affected soil. J Hazard Mater 171:29–37

Lata RK, Divjot K, Yadav AN (2019) Paper: endophytic microbiomes: biodiversity, ecological significance and biotechnological applications

Li J, Chen J, Qu Z, Wang S, He P, Zhang N (2019) Effects of alternating irrigation with fresh and saline water on the soil salt, soil nutrients, and yield of tomatoes. Water 11:1693

Liu Z, Rong Q, Zhou W, Liang G (2017) Effects of inorganic and organic amendment on soil chemical properties, enzyme activities, microbial community and soil quality in yellow clayey soil. PLoS ONE 12:e0172767

Liu J-G, Han X, Yang T, Cui W-H, Wu A-M, Fu C-X, Wang B-C, Liu L-J (2019) Genome-wide transcriptional adaptation to salt stress in Populus. BMC Plant Biol 19:367

Loch DS, Loch RJ (2013) In: Carrow RN, Duncan RR (eds) Best management practices for saline and sodic turfgrass soils: assessment and reclamation. CRC Press (Taylor and Francis Group), Boca Raton

Macias-Benitez S, Garcia-Martinez AM, Caballero Jimenez P, Gonzalez JM, Tejada Moral M, Parrado Rubio J (2020) Rhizospheric organic acids as biostimulants: monitoring feedbacks on soil microorganisms and biochemical properties. Front Plant Sci 11

Maxton A, Singh P, Masih SA (2018) ACC deaminase-producing bacteria mediated drought and salt tolerance in Capsicum annuum. J Plant Nutr 41:574–583

Menezes-Blackburn D, Paredes C, Zhang H, Giles CD, Darch T, Stutter M, George TS, Shand C, Lumsdon D, Cooper P, Wendler R, Brown L, Blackwell M, Wearing C, Haygarth PM (2016) Organic acids regulation of chemical-microbial phosphorus transformations in soils. Environ Sci Technol 50:11521–11531

Millero FJ, Feistel R, Wright DG, McDougall TJ (2008) The composition of standard seawater and the definition of the reference-composition salinity scale. Deep Sea Res Part I 55:50–72

Misra S, Dixit VK, Khan MH, Kumar Mishra S, Dviwedi G, Yadav S, Lehri A, Singh Chauhan P (2017) Exploitation of agro-climatic environment for selection of 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase producing salt tolerant indigenous plant growth promoting rhizobacteria. Microbiol Res 205:25–34

Miyamoto S, Prather RJ, Stroehlein JL (1975) Sulfuric acid and leaching requirements for reclaiming sodium-affected calcareous soils. Plant Soil 43:573–585

Mouhamad R, Mutlag L, Ibrahim K, Jassam O, Mussa R, Iqab M (2017) Reducing water salinity using effective microorganisms

Mtolera I, Dongli S (2018) Effect of effective microorganism and gypsum amendments on nutrient leaching, pH, electrical conductivity, and Okra growth parameters under coastal saline soil. Commun Soil Sci Plant Anal 49:2327–2337

Munns R, James RA, Xu B, Athman A, Conn SJ, Jordans C, Byrt CS, Hare RA, Tyerman SD, Tester M, Plett D, Gilliham M (2012) Wheat grain yield on saline soils is improved by an ancestral Na^+ transporter gene. Nat Biotechnol 30:360–364

Naamala J, Smith DL (2020) Relevance of plant growth promoting microorganisms and their derived compounds, in the face of climate change. Agronomy 10:1179

Naveed M, Mehboob I, Shaker MA, Hussain MB, Farooq M (2015) Biofertilizers in Pakistan: initiatives and limitations. Int J Agric Biol 17:411–420

Norlyn JD (1980) Breeding salt-tolerant crop plants. In: Rains DW, Valentine RC, Hollaender A (eds) Genetic engineering of osmoregulation: impact on plant productivity for food, chemicals, and energy. Springer US, Boston, pp 293–309

Oh D-H, Leidi E, Zhang Q, Hwang S-M, Li Y, Quintero FJ, Jiang X, D'Urzo MP, Lee SY, Zhao Y, Bahk JD, Bressan RA, Yun D-J, Pardo JM, Bohnert HJ (2009) Loss of halophytism by interference with SOS1 expression. Plant Physiol 151:210–222

Park J, Cho KH, Ligaray M, Choi M-J (2019) Organic matter composition of manure and its potential impact on plant growth. Sustainability 11:2346

Paterson AH, Freeling M, Sasaki T (2005) Grains of knowledge: genomics of model cereals. Genome Res 15:1643–1650

Patishtan J, Hartley TN, Fonseca de Carvalho R, Maathuis FJM (2018) Genome-wide association studies to identify rice salt-tolerance markers. Plant Cell Environ 41:970–982

Pérez Escolar R (1966) Reclamation of a saline-sodic soil by use of molasses and distillery slops. J Agric Univ Puerto Rico 50:209–217

Quan R, Wang J, Hui J, Bai H, Lyu X, Zhu Y, Zhang H, Zhang Z, Li S, Huang R (2018) Improvement of salt tolerance using wild rice genes. Front Plant Sci 8

Razzaque S, Elias SM, Haque T, Biswas S, Jewel GMNA, Rahman S, Weng X, Ismail AM, Walia H, Juenger TE, Seraj ZI (2019) Gene expression analysis associated with salt stress in a reciprocally crossed rice population. Sci Rep 9:8249

Rengasamy P (2006) World salinization with emphasis on Australia. J Exp Bot 57:1017–1023

Rengasamy P (2010) Soil processes affecting crop production in salt-affected soils. Funct Plant Biol 37:613–620

Rouphael Y, Cardarelli M, Rea E, Colla G (2012) Improving melon and cucumber photosynthetic activity, mineral composition, and growth performance under salinity stress by grafting onto Cucurbita hybrid rootstocks. Photosynthetica 50:180–188

Ruppel S, Franken P, Witzel K (2013) Properties of the halophyte microbiome and their implications for plant salt tolerance. Funct Plant Biol 40:940–951

Sadiq M, Hassan G, Mehdi SM, Hussain N, Jamil M (2007) Amelioration of saline-sodic soils with tillage implements and sulfuric acid application. Pedosphere 17:182–190

Santos J, Al-Azzawi M, Aronson J, Flowers TJ (2016) eHALOPH a database of salt-tolerant plants: helping put halophytes to work. Plant Cell Physiol 57:e10

Santosh Kumar VV, Verma RK, Yadav SK, Yadav P, Watts A, Rao MV, Chinnusamy V (2020) CRISPR-Cas9 mediated genome editing of drought and salt tolerance (OsDST) gene in indica mega rice cultivar MTU1010. Physiol Mol Biol Plants 26:1099–1110

Sarkar A, Pramanik K, Mitra S, Soren T, Maiti TK (2018) Enhancement of growth and salt tolerance of rice seedlings by ACC deaminase-producing Burkholderia sp. MTCC 12259. J Plant Physiol 231:434–442

Scheben A, Batley J, Edwards D (2018) Revolution in genotyping platforms for crop improvement. Adv Biochem Eng Biotechnol 164:37–52

Seleiman MF, Kheir AMS (2018) Saline soil properties, quality and productivity of wheat grown with bagasse ash and thiourea in different climatic zones. Chemosphere 193:538–546

Sevostianova E, Leinauer B, Sallenave R, Karcher D, Maier B (2011) Soil salinity and quality of sprinkler and drip irrigated warm-season turfgrasses. Agron J 103:1773–1784

Sgroy V, Cassán F, Masciarelli O, Del Papa MF, Lagares A, Luna V (2009) Isolation and characterization of endophytic plant growth-promoting (PGPB) or stress homeostasis-regulating (PSHB) bacteria associated to the halophyte Prosopis strombulifera. Appl Microbiol Biotechnol 85:371–381

Shahid SA, Zaman M, Heng L (2018) Soil salinity: historical perspectives and a world overview of the problem. In: Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques. Springer International Publishing, Cham, pp 43–53

Shivakumar S, Bhaktavatchalu S (2017) Role of plant growth-promoting rhizobacteria (PGPR) in the improvement of vegetable crop production under stress conditions. In: Zaidi A, Khan MS (eds) Microbial strategies for vegetable production. Springer International Publishing, Cham, pp 81–97

Shultana R, Tan Kee Zuan A, Yusop MR, Mohd Saud H, Ayanda AF (2020) Effect of salt-tolerant bacterial inoculations on rice seedlings differing in salt-tolerance under saline soil conditions. Agronomy 10:1030

Sidhu M, Iqbal M, Malik AA, Subhani KM (2009) Role of effective micro-organisms (EM) technology in soil reclamation and crop production. Pak J Water Resour 13:25–30

Singh R, Shelke G, Kumar A, Jha P (2015) Biochemistry and genetics of ACC deaminase: a weapon to “stress ethylene” produced in plants. Front Microbiol 6

Solis CA, Yong MT, Vinarao R, Jena K, Holford P, Shabala L, Zhou M, Shabala S, Chen Z-H (2020) Back to the wild: on a quest for donors toward salinity tolerant rice. Front Plant Sci 11

Sparks DL (2003) 10—the chemistry of saline and sodic soils. In: Sparks DL (ed) Environmental soil chemistry, 2nd edn. Academic Press, Burlington, pp 285–300

Sun Y-P, Yang J-S, Yao R-J, Chen X-B, Wang X-P (2020) Biochar and fulvic acid amendments mitigate negative effects of coastal saline soil and improve crop yields in a three year field trial. Sci Rep 10:8946

Tejada M, Garcia C, Gonzalez J, Hernandez M (2006) Use of organic amendment as a strategy for saline soil remediation: influence on the physical, chemical and biological properties of soil. Soil Biol Biochem 38:1413–1421

Tingwu L, Juan X, Guangyong L, Jianhua M, Jianping W, Zhizhong L, Jianguo Z (2003) Effect of drip irrigation with saline water on water use efficiency and quality of watermelons. Water Resour Manage 17:395–408

Varshney RK, Hoisington DA, Tyagi AK (2006) Advances in cereal genomics and applications in crop breeding. Trends Biotechnol 24:490–499

Wang L, Sun X, Li S, Zhang T, Zhang W, Zhai P (2014) Application of organic amendments to a coastal saline soil in north China: effects on soil physical and chemical properties and tree growth. PLoS ONE 9:e89185

Wichern F, Islam MR, Hemkemeyer M, Watson C, Joergensen RG (2020) Organic amendments alleviate salinity effects on soil microorganisms and mineralisation processes in aerobic and anaerobic paddy rice soils. Front Sustain Food Syst 4

Wu Y, Li Y, Zheng C, Zhang Y, Sun Z (2013) Organic amendment application influence soil organism abundance in saline alkali soil. Eur J Soil Biol 54:32–40

Wu H, Wu L, Zhu Q, Wang J, Qin X, Xu J, Kong L, Chen J, Lin S, Umar Khan M, Amjad H, Lin W (2017) The role of organic acids on microbial deterioration in the Radix pseudostellariae rhizosphere under continuous monoculture regimes. Sci Rep 7:3497

Xie Y, Feng Y, Chen Q, Zhao F, Zhou S, Ding Y, Song X, Li P, Wang B (2019) Genome-wide association analysis of salt tolerance QTLs with SNP markers in maize (Zea mays L.). Genes Genomics 41:1135–1145

Yamada K, Xu H-L (2001) Properties and applications of an organic fertilizer inoculated with effective microorganisms. J Crop Prod 3:255–268

Zhang F, Zhu G, Du L, Shang X, Cheng C, Yang B, Hu Y, Cai C, Guo W (2016) Genetic regulation of salt stress tolerance revealed by RNA-Seq in cotton diploid wild species, Gossypium davidsonii. Sci Rep 6:20582

Zhang A, Liu Y, Wang F, Li T, Chen Z, Kong D, Bi J, Zhang F, Luo X, Wang J, Tang J, Yu X, Liu G, Luo L (2019) Enhanced rice salinity tolerance via CRISPR/Cas9-targeted mutagenesis of the OsRR22 gene. Mol Breeding 39:47

Dr. Tahir is a scientist based in the Molecular and Digital Breeding group at the New Zealand Institute for Plant and Food Research Limited. His expertise involves genomics and identification of molecular and genetic permutations governing biotic and abiotic interactions in plants. His major research areas are centered around polyploid genetics, polygenic traits, disease resistance, resolving complex gene variations and key traits towards development and abiotic and biotic stress tolerance.

Dr. Belgacem holds a Ph.D. in Biological Sciences and a M.Sc. in Natural Resources Management. His experience extends to more than 25 years in the area of arid and desert ecosystems in the MENA region. He joined the Food and Agriculture Organization of the United Nations (FAO) in Saudi Arabia as a Technical Adviser in November 2020. During 2011–2020, he was Rangeland Senior Scientist cum Regional Coordinator of the ICARDA program in the Arabian Peninsula (Dubai Office). He also served as a Head of the Rangeland Program and Director of Plant resources at The Arab Center for the Studies in Arid Zones and Dry Lands (ACSAD), Damascus, and Head of the Rangeland and Mapping Unit in the Institute of Arid Areas (IRA), Tunisia. He coordinated/participated in several research projects with the German Technical Cooperation (GIZ), European Union, IFAD, AFESD, ACSAD, FAO, OSS, and GCC on natural resources management, biodiversity conservation, combating desertification and adaptation to climate change, and rehabilitation and management of rangelands. He published more than 120 scientific research papers.

Dr. Jibran is a scientist based in the Plant Development team at the New Zealand Institute for Plant and Food Research Limited. She is an expert in the field of plant flowering and architectural traits of higher and lower plants. Her key interests in research involve pigment and cell wall biology, as well as stress-associated senescence, to answer fundamental questions in the evolution of plant tolerance in various environments.

Crop Diversification Using Saline Resources: Step Towards Climate-Smart Agriculture and Reclamation of Marginal Lands

Irfan Aziz, Amtul Mujeeb, Azaiez Ouled Belgacem, and Mirza Barjees Baig

Abstract Global climatic changes have influenced world biodiversity and ecosystems. Massive industrialization, deforestation, and pollution have accelerated the process resulting in land degradation and major crop losses and limiting food resources. Extreme climate variability and change have directly impacted on crop production. These changes include the rise of temperature and intermittent rainfall and drought. Global climatic challenges in tandem with the reduction of freshwater resources, soil salinization, and expanding salinity due to erroneous irrigation techniques have exacerbated the problems of productive land degradation. Countries existing in arid climates (such as in the Gulf region), including Pakistan, are prone to face food insecurity as a consequence of fluctuating market prices owing to huge rates of food import. With an ever-increasing population, there has been a significant rise in starvation with estimates indicating a 25–75% increase in production to fulfill food demand. Considering these facts, effective measures are needed to feed the world population. However, this would necessitate well-planned system. This chapter highlights the conceivable outcomes of climate-smart agriculture and reclamation of marginal lands by using saline resources. Recent studies suggested that crop diversification (non-conventional agriculture) using natural saline resources may provide a solution to feed the livestock besides helping in land reclamation. Research on salt and drought resisting plants points toward crop halophytism that may assist in achieving the essential targets. The ability of halophytes to adapt to climatic changes

I. Aziz (✉) · A. Mujeeb
Dr. Muhammad Ajmal Khan Institute of Sustainable Halophyte Utilization, University of Karachi, Karachi 75270, Pakistan
e-mail: irfanaziz@uok.edu.pk

A. O. Belgacem
Food & Agriculture Organization of the United Nations (FAO), Riyadh, Saudi Arabia
e-mail: Azaiez.OuledBelgacem@fao.org

M. B. Baig
Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riyadh, Saudi Arabia
e-mail: mbbaig@ksu.edu.sa

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_21

and human activities has been discovered, which could aid in the global fight against hunger. The removal of salts and trace metals, as well as intercropping halophytes with traditional crops for diverse ecological and economic goals on degraded lands, has been studied.

Keywords Desert-based aquaculture · Developmental initiatives · Droughts · Rural extension · Water harvesting · Water scarcity

1 Introduction

1.1 Climate Change—A Global Conundrum

Over the last few decades, unprecedented global climatic changes have posed a constant danger to world biodiversity and ecosystems. Rapid industrialization, burning of fossil fuels, and increased atmospheric greenhouse gases (GHGs) have expedited these processes. Massive forest destruction, combined with excessive utilization of fossil fuels, has boosted atmospheric CO_2 levels from 280 to 400 μmol L^{-1} with ~800 μmol L^{-1} expected by the end of this century (Raza et al. 2019). Emissions of gases, such as CO_2 and chloro-fluorocarbons (CFCs), in the atmosphere are the primary causes for the greenhouse effect, which has resulted in an increase of average global temperatures (FAO 2018). Soil salinization and environmental pollution, caused by erroneous irrigation techniques and overuse of chemicals (e.g., fertilizers, pesticides, etc.) and driven by climate change, have created havoc resulting in species extinction and limitation of crops and other food resources (Mujeeb et al. 2021). Frequent flooding, drought, and salinity have become problems in agriculture areas.

1.2 Impact of Climate Change on Food Production

The changing nature of climatic variability along with rising global population (which is anticipated to be 9.7 billion by 2050) has not only disrupted ecosystems, but also the food web affecting a wide range of organisms. As per reports of Food and Agriculture Organization (FAO 2018), global hunger is continuously rising since 2014 and climate change is one of the leading drivers behind this crisis. Over the years, the world is experiencing increased events of drought, rainfalls, temperature fluctuations, and salinity which are damaging crops and decreasing their productivity (Rosenzweig et al. 2014). It is estimated that global warming will result in higher evapotranspiration rates causing intense precipitation over many areas of the world (Seneviratne et al. 2012). Because of extreme rainfall events, larger proportions of quick flow would accelerate heavy metal leaching to surface waters (Wijngaard et al. 2017). Therefore, controlling discharges from agriculture has also become a food-security concern.

Pakistan is also facing the effects of climate change with terribly high impact per capita on agriculture (Hussain et al. 2019). The country is facing the brunt of climatic variations with shrinkage in hydrological reserves, glacier melting, floods, and droughts (Chaudhry et al. 2009). The average temperature has risen from 0.9 to 1.5 °C with worst drought episodes in 1998 and 2004 (Hussain and Mumtaz 2014). Sizzling temperatures, severe drought, salinization, pest diseases, and health-related problems have directly affected the livestock reserves, and massive floods in Sindh and Punjab have displaced several people in the recent past. Climate change is negatively affecting the agricultural systems. Therefore, low input sustainable agriculture (LISA) is proposed as a viable option (Sarkar et al. 2020).

According to the Intergovernmental Panel on Climate Change (IPCC) (2007) and Rijal (2019), about 40 to 70% of the flora and fauna are at risk of extinction. The extreme variability in climatic events in the recent past has directly resulted in lesser crop production. The Global Dryland Alliance Countries (GDLA) are also facing competition between food production and biofuel overexploitation at the cost of prime land (Shahid and Al-Shankiti 2013). Furthermore, rising temperatures have affected negatively on crop yields (Zhao et al. 2017). A baseline data of 2014 suggests that, by 2050, an increase in 25–70% crop production will be required to fulfill the demand of food and feed for an ever-increasing human population (Hunter et al. 2017). Emissions from food production create a vicious cycle as the hotter the earth gets the more difficulty the farmers face and they are forced to clear more land to grow more food. Therefore, the sustainability attributes of agroforestry and carbon sequestration have immense potential in mitigating climate change (Rijal 2019).

1.3 Malpractices in Agriculture and Land Degradation

Global climatic challenges in tandem with the reduction in freshwater resources and false irrigation practices have contributed to soil salinization and land degradation, especially in arid and semi-arid regions of the world, including Pakistan. Moreover, the misuse of natural resources (e.g., fresh water and soil and the overuse of fertilizers, pesticides, and herbicides) has been increased substantially. The dearth of freshwater coupled with the brackish nature of ground water has contributed to soil deterioration. Increasing global agricultural production, altering food demand patterns, and reducing food waste and loss are needed shifts, otherwise achieving the goal of a 25–70% increase in crop production would become extremely challenging (Anderson et al. 2019). While non-climatic stresses (e.g., poverty, limited access to resources, food security, environmental degradation, and risks from natural hazards, etc.) are continuously rising with global population, climatic changes-related stresses will also amplify over time (Yohe et al. 2007). Non-climatic as well as climatic stresses would further deplete freshwater resources and, in some areas, would likely increase hunger which will affect 200–600 million people by 2080. Similarly, 2–7 million human population near the coasts will face frequent flooding due to the sea-level rise (Arnell et al. 2002).

To tackle these issues and ensure food security, there is a need to search for new avenues by introducing some climate-smart crop cultivars. Currently, the main task is lessening the pressure on food security (Raza et al. 2019) as the climatic factors with current cropping schemes have worsened crop production (Reckling et al. 2018). Because of increased events of drought, salinity, climate change, and population growth, halophytes seem a plausible choice that may solve the problems of inadequate supply of food, low calories, proteins, fats, and nutrients to the poor people (Cheeseman 2016). The introduction of some new crops, keeping in mind the ecological conditions in arid and semi-arid regions, is the need in current situation. The main question though remains, whether halophytes would be useful in combating food shortage and provide food security to people living in harsh climatic conditions? To answer this question, crop diversification (non-conventional agriculture), using salt and drought resisting plants (Hussain et al. 2020), phytoremediation of metal and salt affected lands (Manousaki and Kalogerakis 2011; Hasanuzzaman et al. 2014; Mujeeb et al. 2020), and crop halophytism are discussed which may be helpful in achieving the required goals (Liu et al. 2020; Liu and Wang 2021). This chapter highlights some important aspects of how to use them to meet the demand both at local and global levels besides ensuring food security, using properly planned system. The possibilities of climate-smart agriculture and reclamation of marginal lands by using saline resources have been also discussed.

2 Crop Diversification Using Saline Resources: Halophytes as a Climate-Smart Option

Because of climatic changes, crop diversification systems using drought and salt-tolerant plants are the key to future agricultural and economic growth in arid and semi-arid regions. Such plants may be used where brackish water is available or saline aquifers are pumped for irrigation. These systems include sustainable management of land resources, productivity enhancement using ecological practices to increase soil fertility of marginal lands, and phytoremediation for diversified climate-smart agriculture (CSA) (Hussain et al. 2020). Since global warming is continuously growing along with frequent droughts and flooding and the pressure on freshwater and land resources is increasing, halophytes may be grown on dry and saline soils. Moreover, a few of them may also tolerate waterlogged conditions which would be helpful in areas facing frequent flooding. Due to their unique morphological and physiological characteristics, halophytes could thrive in such harsh environments making them suitable for CSA (Fig. 1). These plants of the wild are adapted to extreme drought, salinity, water logging, etc., and could be used as alternative food resources, for phytoremediation and various other purposes which are discussed below.

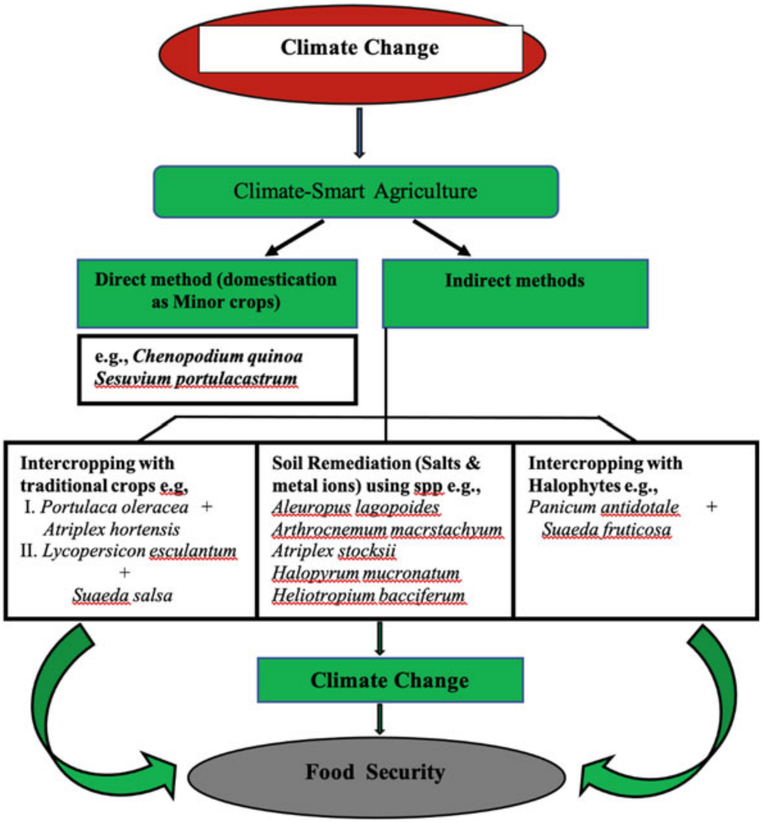


Fig. 1 Schematic diagram showing use of halophytes in CSA

2.1 Making Devastated Saline and Polluted Lands Reusable by Cultivating Halophytes (Land Reclamation)

Continuously decreasing cultivable lands have resulted in major economic penalties worth billions of dollars at the global levels (He et al. 2013). Pollution owing to the disposal of municipal wastes, the use of irrigation water with industrial effluents, the agricultural use of sewage sludge, mining, smelting, and sedimentation, along with secondary salinization, have resulted in huge crop losses in agricultural settings (Möller et al. 2005; Kasassi et al. 2008; Aziz and Khan 2014). Extreme rainfall events have further compounded the problem of an overflow of trace metals in agricultural settings, especially in urban areas. The twin menace of pollution and soil salinization has caused the devastation of lands that were once productive. Therefore, land reclamation is very important for crop production and for meeting the demand of food shortage. Since most of the conventional methods of salt and metal-ion remediation for land reclamation are costly and difficult to operate, e.g., solidification, leaching, etc. (Manousaki and Kalogerakis 2011), phytoremediation seems a better option for the purpose (Hasanuzzaman et al. 2014; Mujeeb et al. 2021). However, differences in habitats require strategic planning while selecting suitable plants in dry, waterlogged, and saline conditions for explicit use.

A few examples of halophytes are listed in Table 1, which may be used on different habitats for removing salts and cleaning trace metals. Some of the listed plants are also found in Pakistan that may help in soil reclamation (Mujeeb et al. 2020, 2021). These plants—*Aeluropus lagopoides*, *Atriplex stocksii*, *Arthrocnemum macrostachyum*, *Halopyrum mucronatum*, *Heliotropium bacciferum,* etc.—have the potential to remove salts and different trace metals from the soil and may help in restoring agricultural lands. For example, *Sesuvium portulacastrum* (L.) L. has the ability to remove huge amount of Pb (1400 mg kg^{-1}) besides absorbing Na^{+} from wetlands (Zaier et al. 2010). Such species would help in revamping saline and waterlogged soils which could be properly utilized for standing crops. Similarly, *Salicornia europea* L. may remove multiple hazardous elements (Pb, Cd, As, etc.) along with salts (Milić et al. 2012). Shoot metal accumulators in general with high biomass yield may be harvested multiple times for the purpose of phytoremediation. For drylands, there are some drought resistant species with the natural ability to survive on salt flats and dunes (Mujeeb et al. 2020). These species include both shrubs and grasses, e.g., *Salsola imbricata* Forssk., *H. bacciferum* Forssk., and *H. mucronatum* (L.) Stapf. Even some of the tree species occurring in deserts, e.g., *Salvadora persica* L. (Panda et al. 2013) and *Tamarix aphylla* (L.), Karst (Hagemeyer and Waisel 1988), could be grown on marginal lands with limited water supply (Table 1).

One of the advantages of growing halophyte species in harsh climatic conditions is their ability to remove more than one element at a time, while consuming little amount of water. Careful selection of such species on different habitats may be useful in land reclamation for crop cultivation. Species with the hyperaccumulating potential of trace metals (with unusually high concentrations) may be solely used for land reclamation while those absorbing metals from the rhizosphere, but with low translocation toward shoot, may be potentially used as alternative source of forage, fodder, and medicines (Mujeeb et al. 2021). For instance, species like *S. persica* with low metal concentration in shoots, fruits, and seeds may be rendered useful for human consumption.

2.2 Intercropping of Halophytes with Food Crops

In view of depleting freshwater resources and increasing soil salinity, intercropping of salt-tolerant plants with conventional crops appears cost-effective and reliable technique for stabilizing the growth and yield in arid regions (Zörb et al. 2019). The selection of suitable species and their management is of great importance that not only improves crop production efficacy but also helps reduce soil salinity (Ghaffarian et al. 2020). Intercropping with the help of polyculture in fields could be a prospective model in combating problems related to future climate changes. The system of using

Table 1 List of some potential halophytes which may be used for soil remediation

Habitat type	Plant species	Soil remediation for Na^+ and other metalloids	References
Salt Marshes	*Avicennia marina*	Mn, Pb, Zn, Fe, and Na^+	Ismail et al. (2014); Kaewtubtim et al. (2016); Mujeeb (2021)
	A. macrostachyum	Mn, Pb, Zn, Fe, As, and Na^+	Martínez-Sánchez et al. (2012); Lu et al. (2017)
	A. lagopoides	Mn, Pb, Zn, Cr, Fe, and Na^+	Ahmed et al. (2013); Mujeeb et al. (2021)
	Phragmites karka	Pb and Cr	Kaewtubtim et al. (2016)
	P. australis	Cr	Calheiros et al. (2008)
	S. europea	Pb, Cd, As, and Fe	Milić et al. (2012)
Tidal Flats	*Atriplex halimus*	Cd, Cr, and Na^+	Bareen and Tahira (2011)
	A. stocksii	Zn, Pb, Fe, Cr, and Na^+	Mujeeb et al. (2021)
	Cressa cretica	Zn, Pb, and Na^+	Mujeeb et al. (2021)
	Polygonum aviculare	Pb, Cu, and Na^+	Liu et al. (2016)
	S. portulacastrum	Pb, Cd, and Na^+	Ghnaya et al. (2005); Zaier et al. (2010)
	Salsola kali	Cd, Fe, Pb, Cr, and Na^+	de la Rosa et al. (2004); Dragovic et al. (2014)
Dunes and salt flats	*H. mucronatum*	Fe, Pb, Zn, Cr, and Na^+	Mujeeb et al. (2020)
	H. bacciferum	Zn, Fe, Pb, and Na^+	Mujeeb (2021)
	Ipomea pes-caprae	Zn, Pb, and Cr	Kaewtubtim et al. (2016); Cordova (2020)
	S. imbricata	Mn, Pb, and Na^+	Mujeeb et al. (2020); Afsar et al. (2021)
	S. persica	Pb	Panda et al. (2013)
	T. aphylla	Cd	Hagemeyer and Waisel (1988)

mixed crops has great potential in the alleviating salt stress particularly in those areas where crop production is a major concern. Halophytes benefit such systems due to the ability of accumulating Na^+ and Cl^- which may be effectively used for removing salts from the soil environment and help in mitigating the effect of osmotic stress imposed on the cash crops (Simpson et al. 2018).

Research on saltwort (*Suaeda salsa*) intercropped with tomato (*Lycopersicon esculentum*) indicated that tomato was able to minimize Na^+ concentrations in the foliage when grown with saltwort from the growing medium (Albaho and Green 2000). ZuccaRini (2008) also observed in an experiment that Na^+ concentrations in tomatoes were decreased and their overall growth was improved when intercropped with halophytes, purslane (*Medicago sativa*), and garden orache (*Atriplex*). Plot experiments on *Kochia scoparia*, *Sesbania sesban*, and Guar (*Cyamopsis tetragonoloba*) indicated that under highly saline conditions (14 dS m^{-1}), monoculture of species resulted in lower biological yields compared to the intercropping, whereby not only an improvement in plant growth was found but the technique also improved salt tolerance at the physiological levels (Ghaffarian et al. 2020). In another instance, mixed cropping of ice plant, i.e., *Mesembryanthemum crystallinum*, a desert native halophyte and cowpea (*Vigna unguiculata*) showed better growth and yield under highly saline conditions (100–300 mM NaCl) compared to monoculture studies (Nanhapo et al. 2017). Plants not only increased their net photosynthesis but also increased their overall shoot biomass indicating that mixed cropping helped in mitigating the damage and growth inhibition of cowpea under various salinity regimes. Some of the promising results of intercropping halophytes with conventional crops are given in Table 2 which helps increasing plant resilience via different morphological and physiological adaptations. Trials on intercropping showed promising results; however, to test the effectivity of such cropping systems on salt resistance mechanisms, experiments with prolonged exposure of plants to salinity are needed. Since most of the studies on mixed cropping (highlighted in Table 2) are either based on one-time trial or experiments during one season, detailed studies are recommended by researchers. These include field evaluation considering different models of intercropping techniques and physiological performance of the plants, their salt sequestering ability, excretion via leaves/foliage, and other biochemical parameters under different salinity regimes. For a better understanding of eco-physiological aspects of growth and plant yields, studies under both lab and field conditions are also recommended.

2.3 Intercropping of Non-conventional Forage Crops

With the increasing population, a significant rise in livestock and meat/milk production has been observed at the global level. However, the availability of quality forage for cattle to fulfill the current demand is lessening. Hence, there is a need to find alternate systems for increasing forage production (Khan et al. 2009). Arid and semi-arid areas, such as Arabian Peninsula countries as well as Pakistan, are more vulnerable to climate change (Malik et al. 2012). In some arid zones of Pakistan, such as part of interior Sindh and Balochistan, freshwater availability is a major problem; hence, such areas are mainly affected by climate change and are considered as socio-economically deprived geographical zones (Sarkar et al. 2020). Therefore, there is a need to develop salt-resistant fodder crops which may resolve food-related crisis if saline/brackish water is used. Therefore, it is imperative to identify and develop halophyte crops.

The practice of intercropping began in the mid of 1980s, and since then, many trials have been done. Integrated studies on mixed cropping system are few. There are many species of halophytes, which produce high biomass under saline conditions

Table 2 Examples of some halophytes used for intercropping with conventional crops

Plant species for intercropping	Type of experiments/cropping system	Growth and physiological parameters	References
K. scoparia (halophyte) intercropped with legumes (*S. sesban* + *C. tetragonoloba*)	Plot experiments in saline fields (with monoculture and polyculture)	Improved biological yields in polyculture, increased osmo-tolerance (e.g., proline/sugars, etc.), plant pigments	Ghaffarian et al. (2020)
M. crystallinum (halophyte ice plant) with *cowpea* (*V. unguiculata*)	Plastic trays using monoculture and mixed plants (polyculture) using 0, 100, 200, and 300 mM NaCl	Improved relative yield, relative growth rates, pigments, Na/K ratio in polycultures under saline conditions	Nanhapo et al. (2017)
Gossypium (cotton) + with *S. salsa* (halophyte) *and M. sativa* (alfalfa)	Monocropping cotton (MC), cotton/*S. salsa* (CSSI) intercropping, and cotton/alfalfa (CAI) intercropping systems under film-mulched drip irrigation in saline fields	Root mass density, aboveground biomass increased in intercropping of CSSI and CAI systems compared to MC (monoculture)	Liang and Shi (2021)
Atriplex hortensis (halophyte) *with Citrullus lannatus* (melon) and *Portulaca oleracea* (purslane)	Both greenhouse and field trials with monoculture of melon and intercropping with Atriplex and purslane	Growth under saline conditions improved in *Atriplex* while Na absorption in purslane. However, yield of purslane was improved in polyculture compared to monoculture	Simpson et al. (2018)

(Khan et al. 2020). Hence, many researchers are now focusing on introducing and developing non-conventional plants as fodder crops across the globe (Liu and Wang 2021) and have partially or completely replaced regular crops with different halophyte species. A few examples from the past include studies on *Distichlis spicata* (Yensen 2006) and *Diplachne fusca* (Kallar grass) (Malik et al. 1986). Halophytic plants, such as *Leptochloa fusca* (sensu lato *D. fusca*), known for excreting salts from the saline soils besides contributing to more stable organic fraction due to slow decomposition, have been successfully grown (Malik et al. 1986). In view of the above-mentioned trials, a sustainable cropping system has been devised for cattle forage as a successful model that consists of *Panicum turgidum* (later described as *Panicum antidotale*) and a salt-succulent halophyte, *Suaeda fruticosa* (Khan et al. 2009). This intercropping has acclaimed worldwide recognition for its unique plot planting, in which salt accumulator (*S. fruticosa*) was grown on crests and *P. turgidum* in place of maize as cattle fodder. The system not only proved beneficial for improving growth of fodder grass, but also removing salts from the saline soils. Since growth of *P. antidotale* usually results in increasing soil salinity, the intercropping with *S. fruticosa* helped in maintaining soil salinity for long. Moreover, *S. fruticosa* may also be used as silage for animals after ensilage process. Since *P. antidotale* is a perennial grass, it may be harvested several times during the same year with yields of about 60,000 kg/ha/year and that too without seed sowing, which is an added benefit. Since it is challenging to convince farmers for introducing or growing new feed, special care was taken to involve them in the decision-making process and they accepted *Panicum* as a fodder crop (Khan et al. 2009). Moreover, animal trials were also undertaken which made the farmers realize the importance of such non-conventional crops. Although there are few instances on such trials, the one discussed in Sect. 2.2 (*K. scoparia* grown in combination with *S. sesban* and *C. tetragonoloba* in polyculture) may be used as model for improving crop yield (Ghaffarian et al. 2020). Based on such findings, experimenting with other salt-tolerant shrubs and perennial grasses with variable agronomic practices may be helpful in developing more salt-tolerant crops for the future.

2.4 Salt- and Drought-Resistant Plants as Minor Crops

The development of local halophytic crops has now been in practice since the last decades. The concept is not very recent, but the progress has been rather slow (Qureshi and Barret-Lennard 1998; Glenn et al. 1999; Yensen 2006; Rozema and Flowers 2008). The domestication of halophytes as ‘new’ or ‘minor’ crops with the help of saline water irrigation on salty soils has been recommended by Khan et al. (2020) given its multiple benefits and its potential to ensure food security. The economic potential of halophytes due to productivity in highly saline conditions and low water irrigation along with nutritional value (protein, lipids, mineral content, etc.) and bioactive compounds makes them a good choice (Agudelo et al. 2021). Many drought- and salt-tolerant species are of great potential as food sources. For instance, the cultivation of Quinoa (*Chenopodium quinoa*), a well-known indigenous species from Bolivia, has rapidly expanded in many areas of the world due to its acceptance as a nutritious crop (Cheeseman 2016). The seeds of this species serve as highly nutritious grains rich in vitamins and minerals, while their protein content is more than double compared to rice (Liu and Wang 2021). Moreover, several species among halophytes may be used as a good source of plant-driven salts, vegetables, fruits, medicines, animal feed, and biofuel and for greening and coastal protection (Munir et al. 2021). Table 3 highlights the potential uses for some of the cash crop halophytes, which may be directly irrigated with saline water.

Many grasses, shrub, and tree species from Pakistan have also been screened for their economic potential for saline agriculture—such as *A. marina, Acacia ampliceps, P. antidotale*, *L. fusca*, *Tamarix indica*, *A. hortensis, Sporobolus ioclados*, *S. persica*, *A. lagopoides*, *P. karka*—and for their ability to grow well in soils with ECe from 20 dSm^{-1} (≈200–300 mM NaCl) (Ahmed et al. 2013; Baig et al. 2007). Some

Table 3 Examples of some halophytes that may be domesticated as non-conventional cash crops using saline brackish water

Plant species	Uses	References
A. halimus	Leaves as condiments, forage source due to high protein content	Agudelo et al. (2021); Hoi and Hyun (2013)
Atriplex triangularis	More vitamin C than spinach and has many essential elements in stems and leaves. Could be used as high-quality feed for cattle, sheep, and horses. It may be irrigated directly with seawater	Liu and Wang (2021)
A. marina	Seeds (baby nut) as vegetable with high protein, leaves as forage for camels. It may be irrigated directly with seawater	Aziz and Khan (2001)
Cakile maritima	Seed oil for human consumption for high unsaturated fatty acids	Chalbi et al. (2013)
C. quinoa	Nutritious edible seeds due to high minerals and vitamins, protein content is double the amount than rice, and contains lysine, lacking in many grains	Liu and Wang (2021)
P. antidotale	Best alternative as cattle feed due to high mineral content	Khan et al. (2009)
P. karka	Young leaves as fodder, potential biofuel source with high lignocellulosic biomass	Joshi et al. (2018)
P. oleracea	Commonly called purslane and used as smother crop, and as forage	Simpson et al. (2018)
Salicornia fruticosa	Young shoots as vegetables, salt driven from plants used in cooked sausages	Agudelo et al. (2021); Hoi and Hyun (2013)
S. fruticosa	Seed oil containing high unsaturated fatty acids	Hameed et al. (2012); Weber et al. (2007)
S. salsa	Used as vegetables with high mineral content, rich source of vitamins, antioxidants, and dietary fibers	Liu and Wang (2021)
T. indica	Biofuel source for high lignocellulosic biomass	Sun et al. (2011)

of the halophytes have great nutritious value, while others may be used for edible oil, biofuel, and even medicines for having bioactive compounds and antioxidant properties (Table 3). Even some of them can flourish in twice the concentration of seawater salinity, e.g., mangroves which are used as fodder for camels and cattle (Aziz and Khan 2014). In view of significant importance in landscaping and ecological restoration, halophyte gardens are also being constructed in China near the Yellow

River Delta where more than 250 halophytic species have been introduced. These gardens form unique landscapes where almost all species complete their life cycle in saline environments (Liu and Wang 2021). The beneficial properties of halophyte species have made these plants of rising interest as a new food stuff.

3 Crop Halophytism—Future Perspective

The concept of 'crop halophytism' has been evolved following great economic potential of pseudo-cereal 'Chenopodium quinoa' (Liu et al. 2020). The paradigm shift of moving from crop breeding for Na^+ exclusion to breeding for crop halophytism is on the rise, and this concept has given hope to plant breeders as an environmentally sustainable solution for the global food security. Recent advances suggest that the overexpression of *NHX* (Na/H exchanger) and VP_1 (vacuolar) genes, facilitating Na^+ sequestration and maintaining Na/K homeostasis, may be beneficial for improving salt tolerance mechanisms among closely allied species of rice (*Oryza sativa*) using the blueprint of the wild salt-tolerant type of rice, *O. coarctata* (Dassanayake and Larkin 2017). For this purpose, eco-physiological studies on different aspects of allied species are imminent; for example, mechanisms among crop grasses with closely related perennial halophytes are compared. Plant physiologists investigate the processes that are involved in tight control of Na^+ uptake and its sequestration at both plasma membrane and tonoplast (via different transporters), types, and synthesis of compatible osmolytes, reactive oxygen species (ROS) signaling, and detoxification systems in species of interest. Such studies would help understand the underlying mechanisms that may be involved in improving salt tolerance and opening new avenues for 'crop halophytism' in future.

4 Conclusions

In light of climate change, the elements that contribute to the agricultural production methods must be revamped. Cropping system modifications and alterations, such as the use of non-traditional water supplies, the introduction of stress-tolerant crop cultivars, and the use of substitute resources such as halophytes (Hussain et al. 2020), are critical to coping with harsh climatic changes. There are over 400 halophyte species in Pakistan (Khan and Qaiser 2006), and many of them could be used for the reasons listed above. Future cropping studies on these species will be advantageous as climate-smart solutions for agriculture utilizing various methods. Intercropping, land reclamation via soil remediation, and the application of xero-halophytes on dry and saline areas, all have the potential to alleviate drought-related issues. Integrated crop improvement and sustainable production, on the other hand, would necessitate collaboration between farmers, policymakers, and academics to meet the growing demand for food, which appears to be aggravated by global climate change.

References

Afsar S, Aziz I, Qasim M, Baloch AH, Syed MN, Gulzar SG (2021) Salt tolerance of a leaf succulent halophyte *Salsola imbricata*—growth and water relations perspective. Int J Biol Biotech 18(3):499–507

Agudelo A, Carvajal M, Martinez-Ballesta MDC (2021) Halophytes of the Mediterranean Basin—underutilized species with the potential to be nutritious crops in the scenario of the climate change. Foods 2021(10):119. https://doi.org/10.3390/foods10010119

Ahmed MZ, Shimazaki T, Gulzar S, Kikuchi A, Gul B, Khan MA, Watanabe KN (2013) The influence of genes regulating transmembrane transport of Na^+ on the salt resistance of *Aeluropus lagopoides*. Funct Plant Biol 40(9):860–871. https://doi.org/10.1071/FP12346

Albaho M, Green JL (2000) *Suaeda salsa*, a desalinating companion plant for greenhouse tomato. Hort Sci 35:620–623

Anderson WB, Seager R, Baethgen W, Cane M, You L (2019) Synchronous crop failures and climate forced production variability. Sci Adv 5:eaaw1976. https://doi.org/10.1126/sciadv.aaw1976

Arnell NW, Cannell MGR, Hulme M, Ovats RS, Mitchell JFB, Nicholls RJ, Parry ML, Livermore MTJ, White A (2002) The consequences of CO_2 stabilization for the impacts of climate change. Clim Change 53:413–446

Aziz I, Khan MA (2001) Ecophysiology of A. marina populations growing in polluted coasts around Arabian sea. Pak J Bot 33(4):429–441

Aziz I, Khan F (2014) Distribution, ecology and ecophysiology of mangroves in Pakistan. In: Khan MA, Böer B, Öztürk M, Al Abdessalaam TZ, Clüsener-Godt M, Gul B (eds) Sabkha ecosystems. Tasks for vegetation science, vol 47. Springer, Dordrecht, pp 55–66. https://doi.org/10.1007/978-94-007-7411-7_3

Baig MB, Akbar G, Malik AH (2007) Sustainable strategies to reclaim sandy desert of Cholistan—opportunities and perspectives. In: Proceedings of ESDev—2007 CIIT, Pakistan, Abbottabad, pp 1137–1145

Bareen F, Tahira SA (2011) Metal accumulation potential of wild plants in tannery effluent contaminated soil of Kasur, Pakistan: field trials for toxic metal cleanup using *Suaeda fruticosa*. J Hazard Mater 186(1):443–450. https://doi.org/10.1016/j.jhazmat.2010.11.022

Calheiros CSC, Rangel AOSS, Castro PML (2008) Evaluation of different substrates to support the growth of *Typha latifolia* in constructed wetlands treating tannery wastewater over long-term operation. Bioresour Technol 99:6866–6877. https://doi.org/10.1016/j.biortech.2008.01.043

Chalbi N, Hessini K, Gandour M, Mohamed S, Smaoui A, Abdelly C, Youssef A, Ben N (2013) Are changes in membrane lipids and fatty acid composition related to salt-stress resistance in wild and cultivated barley? J Plant Nutr Soil Sci 2013(176):138–147

Chaudhry QZ, Mahmood A, Rasul G, Afzaal M (2009) Climate change indicators of Pakistan. Technical Report no. PMD-22/2009 42

Cheeseman J (2016) Food security in the face of salinity, drought, climate change, and population growth. In: Khan MA, Ozturk M, Gul B, Ahmed MZ (eds) Halophytes food security dry lands. Elsevier Inc., Amsterdam, pp 111–123. https://doi.org/10.1016/B978-0-12-801854-5.00007-8

Cordova MR (2020) A preliminary study on heavy metal pollutants chrome (Cr), cadmium (Cd), and lead (Pb) in sediments and beach morning glory vegetation (*Ipomoea pes-caprae*) from Dasun Estuary, Rembang, Indonesia. Marine Poll Bull 111–819

Dassanayake M, Larkin JC (2017) Making plants break a sweat: the structure, function, and evolution of plant salt glands. Front Plant Sci 8:406. https://doi.org/10.3389/fpls.2017.00724

de La Rosa G, Peralta-Videa JR, Montes M, Parsons JG, Cano-Aguilera I, Gardea-Torresdey JL (2004) Cadmium uptake and translocation in tumbleweed (*Salsola kali*), a potential Cd-hyperaccumulator desert plant species: ICP/OES and XAS studies. Chemosphere 55, 1159–1168. https://doi.org/10.1016/j.chemosphere.2004.01.028

Dragovic R, Zlatkovic B, Dragovic S, Petrovic J, Mandic LJ (2014) Accumulation of heavy metals in different parts of Russian thistle (*Salso tragus*, Chenopodiaceae), a potential hyperaccumulator plant species. Biologica Nyssana 5(2):83–90. http://journal.pmf.ni.ac.rs/bionys/index.php/bionys/article/view/94

FAO (2018) The State of Food Security and Nutrition in the World 2017: Building Resilience for Peace and Food Security; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy

Ghaffarian MR, Yadavi A, Movahhedi Dehnavi M, Dabbagh Mohammadi Nassab A, Salehi M (2020) Improvement of physiological indices and biological yield by intercropping of Kochia (*Kochia scoparia*), Sesbania (*Sesbania aculeata*) and Guar (*Cyamopsis tetragonoliba*) under the salinity stress of irrigation water. Physiol Mol Biol Plants 26(7):1319–1330. https://doi.org/10.1007/s12298-020-00833-y

Ghnaya T, Nouairi I, Slama I, Messedi D, Grignon C, Abdelly C, Ghorbel MH (2005) Cadmium effects on growth and mineral nutrition of two halophytes: *Sesuvium portulacastrum* and *Mesembryanthemum crystallinum*. J Plant Physiol 162:1133–1140. https://doi.org/10.1016/j.jplph.2004.11.011

Glenn EP, Brown JJ, Blumwald E (1999) Salt tolerance and crop potential of halophytes. CRC Crit Rev Plant Sci 18:227–255

Hagemeyer J, Waisel Y (1988) Excretion of ions (Cd_2^+, Li^+, Na^+ and Cl^-) by *Tamarix aphylla*. Physiol Plant 73(4):541–546. https://doi.org/10.1111/j.1399-3054.1988.tb05438.x

Hameed A, Hussain T, Gulzar S, Aziz I, Gul B, Khan MA (2012) Salt tolerance of a cash crop halophyte *Suaeda fruticosa*: biochemical responses to salt and exogenous chemical treatments. Acta Physiol Plant 34:2331–2340. https://doi.org/10.1007/s11738-012-1035-6

Hasanuzzaman M, Nahar K, Alam MM, Bhowmik PC, Hossain MA, Rahman MM, Prasad MNV, Ozturk M, Fujita M (2014) Potential use of halophytes to remediate saline soils. Biomed Res Int 2014:589341. https://doi.org/10.1155/2014/589341

He B, Yun Z, Shi J, Jiang G (2013) Research progress of heavy metal pollution in China: sources, analytical methods, status, and toxicity. Chinese Sci Bullet 58(2):134–140. https://doi.org/10.1007/s11434-012-5541-0

Hoi KD, Hyun KT (2013) *Salicornia* spp.-derived salt and its production process. U.S. Patent No 8,420,152

Hunter MC, Smith RG, Schipanski ME, Atwood LW, David AM (2017) Agriculture in 2050: recalibrating targets for sustainable intensification. Bioscience 67(4):386–391. https://doi.org/10.1093/biosci/bix010

Hussain M, Mumtaz S (2014) Climate change and managing water crisis: Pakistan's perspective. Rev Environ Health 29:71–77. https://doi.org/10.1515/reveh-2014-0020

Hussain M, Butt AR, Uzma F, Ahmed R, Irshad S, Rehman A, Yousaf B (2019) A comprehensive review of climate change impacts, adaptation, and mitigation on environmental and natural calamities in Pakistan. Environ Monit Assess (2020)192:48. https://doi.org/10.1007/s10661-019-7956-4

Hussain MI, Farooq N, Muscolo A, Rehman A (2020) Crop diversification and saline water irrigation as potential strategies to save freshwater resources and reclamation of marginal soils—a review. Env Sci Poll Res. https://doi.org/10.1007/s11356-020-09111-6

IPCC. 2007. Climate Change (2007) The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, 996 p

Ismail S, Saifullah SM, Khan SH (2014) Bio-geochemical studies of Indus delta mangrove ecosystem through heavy metal assessment. Pak J Bot 46(4):1277–1285. http://www.pakbs.org/…/17.pdf

Joshi A, Kanthaliya B, Arora J (2018) Halophytes of Thar desert: Potential source of nutrition and feedstuff. Int J Bioassays 8:5674–5683

Kaewtubtim P, Meeinkuirt W, Seepom S, Pichtel J (2016) Heavy metal phytoremediation potential of plant species in a mangrove ecosystem in Pattani Bay, Thailand. Appl Ecol Environ Res 14(1):367–382. https://doi.org/10.15666/aeer/1401_367382

Kasassi A, Rakimbei P, Karagiannidis A, Zabaniotou A, Tsiouvaras K, Nastis A, Tzafeiropoulou K (2008) Soil contamination by heavy metals: measurements from a closed unlined landfill. Biores Technol 99(18):8578–8584. https://doi.org/10.1016/j.biortech.2008.04.010

Khan MA, Qaiser M (2006) Halophytes of Pakistan: characteristics, distribution and potential economic usages. In: Khan MA, Benno B, Kust GS, Barth HJ (eds) Sabkha ecosystems, tasks for vegetation science, vol 42. Springer, Netherlands, pp 129–153. https://doi.org/10.1007/978-1-4020-5072-5

Khan MA, Ansari R, Ali H, Gul B, Nielsen BL (2009) *Panicum turgidum*, a potentially sustainable cattle feed alternative to maize for saline areas. Agric Ecosyst Environ 129:542–546

Khan W-D, Tanveer M, Shaukat R, Ali M, Pirdad F (2020) Salt and drought stress tolerance in plants: signaling and communication in plants. Springer, Berlin. ISBN: 9783030402761

Liang J, Shi W (2021) Cotton/halophytes intercropping decreases salt accumulation and improves soil physicochemical properties and crop productivity in saline-alkali soils under mulched drip irrigation: a three-year field experiment. Field Crops Res 262. https://doi.org/10.1016/j.fcr.2020.108027

Liu L, Wang B (2021) Protection of halophytes and their uses for cultivation of saline-alkali soil in China. Biology 2021(10):353. https://doi.org/10.3390/biology10050353

Liu M, Pan T, Allakhverdiev SI, Yu M, Shabala S (2020) Crop halophytism: an environmentally sustainable solution for global food security. Trends Plant Sci 2020.25(7):630–634. https://doi.org/10.1016/j.tplants.2020.04.008.PMID:32444156

Liu Z, Hamuti A, Abdulla H, Zhang F, Mao X (2016) Accumulation of metallic elements by native species thriving in two mine tailings in Aletai. China Environ Earth Sci 75:781. https://doi.org/10.1007/s12665-016-5594-5

Lu Y, Li X, He M, Zeng F, Li X (2017) Accumulation of heavy metals in native plants growing on mining-influenced sites in Jinchang: a typical industrial city (China). Environ Earth Sci 76(13):446. https://doi.org/10.1007/s12665-017-6779-2

Malik KA, Aslam Z, Naqvi M (1986) Kallar grass. A plant for saline land. Ghulam Ali Printers, Lahore, Pakistan, 93 p

Malik SM, Awan H, Khan N (2012) Mapping vulnerability to climate change and its repercussions on human health in Pakistan. Global Health 8:31. https://doi.org/10.1186/1744-8603-8-31

Manousaki E, Kalogerakis N (2011) Halophytes—an emerging trend in phytoremediation. Int J Phytorem 13(10):959–969. https://doi.org/10.1080/15226514.2010.532241

Martínez-Sánchez MJ, García-Lorenzo ML, Pérez-Sirvent C, Bech J (2012) Trace element accumulation in plants from an aridic area affected by mining activities. J Geochem Explor 123:8–12. https://doi.org/10.1016/j.gexplo.2012.01.007

Milić D, Luković J, Ninkov J, Zeremski-Škorić T, Zorić L, Vasin J, Milić S (2012) Heavy metal content in halophytic plants from inland and maritime saline areas. Cent Eur J Biol 7(2):307–317. https://doi.org/10.2478/s11535-012-0015-6

Möller A, Müller HW, Abdullah A, Abdelgawad G, Utermann J (2005) Urban soil pollution in Damascus, Syria: concentrations and patterns of heavy metals in the soils of the Damascus Ghouta. Geoderma 124(1–2):63–71. https://doi.org/10.1016/j.geoderma.2004.04.003

Mujeeb A, Aziz I, Ahmed MZ, Alvi SK, Shafiq S (2020) Comparative assessment of heavy metal accumulation and bio indication in coastal dune halophytes. Ecotoxicol Environ Saf 195:110486. https://doi.org/10.1016/j.ecoenv.2020.110486

Mujeeb A (2021) Phytoremediation potential of halophytes in coastal and near coastal areas of Karachi. Ph.D. dissertation. Dr. M. Ajmal Khan Institute of Sustainable Halophyte Utilization, University of Karachi, Karachi 75270, Pakistan

Mujeeb A, Aziz I, Ahmed MZ, Shafiq S, Fatima S, Alvi SK (2021) Spatial and seasonal metal variation, bioaccumulation and biomonitoring potential of halophytes from littoral zones of the Karachi Coast. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2021.146715

Munir N, Hasnaina M, Roessnerb U, Abideen Z (2021) Strategies in improving plant salinity resistance and use of salinity resistant plants for economic sustainability. Crit Rev Environ Sci Techhttps://doi.org/10.1080/10643389.2021.1877033etal

Nanhapo PI, Yamane K, Iijima M (2017) Mixed cropping with ice plant alleviates the damage and the growth of cowpea under consecutive NaCl treatment and after the recovery from high salinity. Plant Prod Sci 20(1):111–125. https://doi.org/10.1080/1343943X.2017.1282828

Panda SS, Chaturvedi N, Dhal NK, Rout NC (2013) An assessment of heavy metal accumulation in mangrove species of Bhitarkanika, Odisha, India. Res Plant Biol 3(6):1–5. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.944.1471&rep=rep1&type=pdf

Qureshi RH, Barrett-Lennard EG (1998) Saline agriculture for irrigated land in Pakistan: a handbook, Monograph No 50, Canberra, Australia: Australian Centre for International Agricultural Research (ACIAR), 1–142

Raza A, Razzaq A, Mehmood SS, Zou X, Zhang X, Lv Y, Xu J (2019) Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. Plants 8:34. https://doi.org/10.3390/plants8020034

Reckling M, Döring TF, Bergkvist G, Chmielewski F, Stoddard F, Watson C, Seddig S, Bachinger J (2018) Grain legume yield instability has increased over 60 years in long-term field experiments as measured by a scale-adjusted coefficient of variation. Asp Appl Biol 2018(138):15–20

Rijal S (2019) Agroforestry system: approaches for climate change mitigation and adaptation. Big Data Agric [BDA] 1(2):23–25. https://doi.org/10.26480/bda.02.2019.23.25

Rosenzweig C, Elliott J, Deryng D, Ruane AC, Müller C, Arneth A, Boote KJ, Folberth C, Glotter M, Khabarov N (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc Natl Acad Sci USA 2014(111):3268–3273

Rozema J, Flowers T (2008) Crops for a salinized world. Science 322:1478–1480

Sarkar D, Kar SK, Chattopadhyay A, Rakshit A, Tripathi VK, Dubey PK, Abhilash PC (2020) Low input sustainable agriculture: a viable climate-smart option for boosting food production in a warming world. Ecol Ind 115(2020):106412. https://doi.org/10.1016/j.ecolind.2020.106412

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A, Vera C, Zhang X (2012) Changes in climate extremes and their impacts on the natural physical environment. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change (IPCC). Cambridge University Press, Cambridge, pp 109–230

Shahid SA, Al-Shankiti A (2013) Sustainable food production in marginal lands—case of GDLA member countries. Int Soil Water Conserv Res 1(1):24–38. https://doi.org/10.1016/S2095-6339(15)30047-2

Simpson CR, Franco JG, King SR, Volder A (2018) Intercropping halophytes to mitigate salinity stress in watermelon. Sustainability 10(3):681. https://doi.org/10.3390/su10030681

Sun YC, Wen JL, Xu F, Sun RC (2011) Structural and thermal characterization of hemicelluloses isolated by organic solvents and alkaline solutions from *Tamarix austromongolica*. Biores Technol 102(10):5947–5951. https://doi.org/10.1016/j.biortech.2011.03.012

Weber DJ, Ansari R, Gul B, Khan MA (2007) Potential of halophytes as source of edible oil. J Arid Environ 68:315–321

Wijngaard RR, van der Perk M, van der Grift B, Ton CM, de Nijs M, Bierkens FP (2017) The impact of climate change on metal transport in a lowland catchment. Water Air Soil Pollut 228:107. https://doi.org/10.1007/s11270-017-3261-4

Yensen NP (2006) Halophyte uses for the twenty-first century. Springer, Dordrecht, pp 367–396

Yohe GW, Lasco RD, Ahmad QK, Arnell NW, Cohen SJ, Hope C, Janetos AC, Perez RT (2007) Perspectives on climate change and sustainability. Climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge, UK, pp 811–841

Zaier H, Ghnaya T, Lakhdar A, Baioui R, Ghabriche R, Mnasri M, Sghair S, Lutts S, Abdelly C (2010) Comparative study of Pb-phytoextraction potential in *Sesuvium portulacastrum* and *Brassica juncea*: tolerance and accumulation. J Haz Mater 183(1–3):609–615. https://doi.org/10.1016/j.jhazmat.2010.07.068

Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, Huang M, Yao Y, Bassu S, Ciais P (2017) Temperature increase reduces global yields of major crops in four independent estimates. Proc Natl Acad Sci USA 2017(114):9326–9331

Zörb C, Geilfus CM, Dietz KJ (2019) Salinity and crop yield. Plant Biol (Stuttg). Suppl 1:31–38. https://doi.org/10.1111/plb.12884

ZuccaRini P (2008) Ion uptake by halophytic plants to mitigate saline stress in *Solanum lycopersicon* L., and different effect of soil and water salinity. Soil Water Res 3(2):62–73

Dr. Irfan Aziz is serving as Associate Professor at Dr. Muhammad Ajmal Khan Institute of Sustainable Halophyte Utilization, University of Karachi, Karachi, Pakistan. He obtained his Ph.D. degree in Plant Sciences (Ecophysiology of Mangroves) from the Department of Botany, University of Karachi in 2001 and has been involved in teaching and research for the last 30 years. His major research interests are physiological ecology of halophytes and mangroves, conservation of mangrove ecosystems, desertification control, plant responses to abiotic stresses and adaptation to climate change, rehabilitation and management of wastelands and phytoremediation potential of halophytes. He has more than 40 publications to his credit (Research, Review, and Opinion articles) in the Journals of International repute with an impact factor of 94. He is serving as a Review Editor of several International Journals. He has presented several oral presentations in the International Conferences and symposia besides being part of the organizing committees. He has been a member of different professional societies and Organizations (American Society of Plant Biologists, ISME, WWF, Shehri, Citizens for Better Environment etc.) and is currently a commission member of Mangrove Specialists Group (MSG) at the International Union for Conservation of Nature (IUCN).

Dr. Amtul Mujeeb is a Research Associate at Dr. Muhammad Ajmal Khan Institute of Sustainable Halophyte Utilization, University of Karachi, Pakistan. She has completed her Ph.D. degree on Phytoremediation Potential of Coastal Halophytes. She earned her M.Sc. from the Department of Botany, University of Karachi. Her major research interest is on trace metal phytoremediation potential of halophyte species. She has published five articles (4 research and 1 review articles) in journals of international repute with an impact factor of 33.

Dr. Azaiez Ouled Belgacem holds a Ph.D. in Biological Sciences and a M.Sc. in Natural Resources Management. His experience extends to more than 25 years in the area of arid and desert ecosystems in the MENA region. He joined the Food and Agriculture Organization of the United Nations (FAO) in Saudi Arabia as a Technical Adviser in November 2020. During 2011–2020, he was Rangeland Senior Scientist cum Regional Coordinator of the ICARDA program in the Arabian Peninsula (Dubai Office). He also served as a Head of the Rangeland Program and Director of Plant resources at The Arab Center for the Studies in Arid Zones and Dry Lands (ACSAD), Damascus, and Head of the Rangeland and Mapping Unit in the Institute of Arid Areas (IRA), Tunisia. He coordinated/participated in several research projects with the German Technical Cooperation (GIZ), European Union, IFAD, AFESD, ACSAD, FAO, OSS, and GCC on natural resources management, biodiversity conservation, combating desertification and adaptation to climate change, and rehabilitation and management of rangelands. He has published more than 120 scientific research papers.

Land Use Land Cover Change in Salt Range Wetlands Complex of Pakistan in Response to Climate Change

Syeda Maria Ali, Sehrish Aslam, Aneeza Islam, and Muhammad Afzaal

Abstract Wetlands as natural biomes are threatened globally due to population growth and unsustainable development. The rate and magnitude of climate change have as well major impacts on wetlands and their resources due to changes in the hydrological cycle. A number of wetlands have been replaced to meet the food production demand and agricultural practices in the twentieth century. Pakistan, an arid climate, supports over 7,800,000 ha of inland wetlands and 250,000 ha of coastal mangroves and swamps, of which 225 are of national significance while 19 have been identified as *Ramsar* sites. In this chapter, spatiotemporal changes in Wetland Complex are assessed by the authors in the central north region of the Punjab province of Pakistan, known by the name of Salt Range Wetlands Complex (SRWC). It is a 175 km thrust between the foot hills of Himalayan Mountains and Indus plains extending from *Jhelum* in the east and *Kala Bagh* in the west. This chapter is designed to comprehend the climatic trends of SRWC and spatiotemporal change detection in the area of lakes over the period 1987–2014. Predictive assessment due to changing climate scenarios has also been discussed. The vulnerability of the area toward natural disasters, including droughts and floods, drew our attention to address this topic in response to giving high priority to wetlands for achieving sustainable development goals #2, #6, and #12. An increase in the average annual rainfall pattern from the year 1985 to 2014, while a decrease in temperature and potential evapotranspiration, was observed using the Climate Research Unit (CRU) data. The change detection analysis has revealed the increase in agricultural, uncultivated, built-up areas and water bodies with reduction in forest and scrub area. The expansion in the *Namal* Lake (26 ha), *Jahlar* Lake (3 ha), and *Kallar Kahar* Lake (162 ha) has been examined. However,

S. M. Ali (✉)
Department of Environmental Science, Faculty of Basic and Applied Sciences, International Islamic University, Islamabad, Pakistan
e-mail: maria.ali@iiu.edu.pk

S. Aslam · A. Islam
Department of Environmental Sciences, Faculty of Basic and Applied Sciences, International Islamic University, Islamabad, Pakistan
e-mail: aneeza.phdes47@iiu.edu.pk

M. Afzaal
Research and Development Division, Pakistan Meteorological Department, Islamabad, Pakistan

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_22

Ucchali and *Khabekki* Lakes were compressed to 176 and 120 ha, respectively. Predictions using Representative Concentration Pathways 4.5 and 8.5 reveal stress on water resource in future (2010–2050).

Keywords Change detection · Climate change · Predictive assessment · Remote sensing (RS) · Salt range wetlands complex (SRWC)

1 Introduction

Wetlands are natural biomes besides tropical rainforests that sustain vital provisioning and cultural services while providing the habitat for specific flora and fauna (Gitau et al. 2019; Varghese et al. 2008). Wetlands cover merely 6% of the total area of the Earth's surface, but they have significant importance in biogeochemical and hydrological processes. Wetlands hold the valuable biodiversity and also provide vital services to mankind (James et al. 2019; Junk et al. 2013). Wetlands, the most diverse ecosystem, are threatened due to unsustainable development and population pressure (Sanjerehei and Rundel 2017). Surplus of wetlands has been lost during the twentieth century on account of use as fertile land for cultivation (Jeffries et al. 2016; Qazi et al. 2012). Wetlands, if managed sustainably, are the sinks of carbon and considered as a nature-based mitigation solution of climate change (Taillardat et al. 2019). For instance, improving water holding capacity of lakes and wetlands by dredging or creating new land for plantation through river sedimentation are some of the mitigation responses to cope with environmental and climate changes in the ecosystem (Hossain et al. 2015).

Change in climate variables determines the structure and function of wetland ecosystems (Sanjerehei and Rundel 2017; Desta et al. 2012). The rate and magnitude of climate change could have major impacts on regional water resources due to changes in the hydrological cycle (IPCC 2007). Significant and persistent changes in hydrological regimes, precipitation patterns, temperature/humidity, evaporation/evapotranspiration, and increase in the frequency of extreme climate events such as floods and droughts can alter the runoff and groundwater recharge of wetlands (Sanjerehei and Rundel 2017; Desta et al. 2012). There is a dire need to monitor the variation in the area, structure, and characteristics of wetlands for the conservation and efficient management of these ecosystems (Izhar-uI-Haq and Iqbal 2016; Sanjerehei and Rundel 2017).

Pakistan's arid climate supports over 7,800,000 ha of inland[1] wetlands and 250,000 ha of coastal mangroves[2] and swamps,[3] of which 225 are of national significance while 19 have been identified as Ramsar sites (Nazir et al. 2018; Arshad 2011). Ramsar sites are the wetlands designated to be of international importance according to the Ramsar Convention. There are around 2300 Ramsar sites around the world.

[1] Inland wetlands are floodplain wetlands along rivers which include wet meadows and marshes.

[2] Shrubs or small trees forests grow in the salty or brackish water of coast.

[3] Areas permanently saturated with water; Swamp is a forested wetland.

Total nineteen sites are designated as wetlands in Pakistan that cover 1,343,627 ha area (Okuno et al. 2017). Wetland's significance was the focus of attention for the first time in 1967, and Pakistan became signatory party to Ramsar Convention in 1976. Only nine sites were of global significance in 1976 which increased to 16 sites in 2001, and then, 19 sites were declared as Ramsar sites in 2002 (Khan and Arshad 2014). In the year 2000, Pakistan Wetlands Programme (PWP) was initiated by Worldwide Fund for Nature, Pakistan (WWF-P), with the main aim of conserving the wetlands and the associated biodiversity for 5 years. Later in 2009, a national policy was drafted for the protection of wetlands. The Ministry of Climate Change also made changes in the climate change policy in 2011 to protect, sustain, and enhance the wetlands in Pakistan (Qazi et al. 2012; Qamer et al. 2009).

The rate and extent of Pakistan's wetland loss and degradation are associated with the allocation and distribution of water, construction of dams, barrages, head works, and flow regulation of rivers to meet the water demands for hydroelectricity and irrigation (Khan and Arshad 2014). Population growth, domestic and industrial pollution, use of pesticides, and the lack of public knowledge and awareness are some other reasons of wetlands' degradation in Pakistan. Population growth has an impact on increasing the demand for natural resources that turn out to be at risk due to unsustainable utilization (Hussain 2002). The primary threat to wetlands here is the ignorance about their ecological services (Izhar-uI-Haq and Iqbal 2016). This has resulted in loss of 60% of Pakistan's inland wetlands. Change in climatic variability is also altering the hydrology of a specific wetland (Izhar-uI-Haq and Iqbal 2016; Khan and Arshad 2014). In addition, extreme climate events have been experienced in Salt Range Wetlands Complex (SRWC) in past years; this is evident if we refer to 2010 floods and 2000 droughts (Salma et al. 2012). Lakes in SRWC are brackish to saline inland wetlands that support marshy and aquatic vegetation and are mostly fed by the received rainfall (that increases during monsoon season), by surrounding mountain streams, and by small springs in a small quantity from hills (Ali et al. 2011; Rais et al. 2011). The high global significance of SRWC of Pakistan is due to the diversity of species it supports and services it provides to the people living around. It also contributes to maintaining the temperature and climate of the area.

This study was designed to address the climatic trends of SRWC, spatiotemporal change detection in the area of lakes over the period 1987–2014. Changing climate scenarios and their predictive assessment have also been discussed. SRWC, like other natural ecosystems, is highly affected by the climate vulnerability and extreme events, including droughts and floods. This drew the attention toward this research topic in response to the challenge of achieving sustainability in wetlands under sustainable development goals (SDGs) #2, #6, and #12. The 2030 Agenda targets relating to sustainable development in wetlands are as follows: sustainable food production (Target 2.4); improved water quality (Target 6.3); and sustainable management services (Target 12.2) (Jaramillo et al. 2019; Seifollahi-Aghmiuni et al. 2019; Osborn et al. 2015).

This study aims at assessing the change in wetlands due to climate change in SRWC. The achievement of this objective is done through the use of the following: a spatiotemporal Land Use Land Cover Change (LULC) detection in the study area over the period 1987–2014; an assessment of change in average wetland area based on climatic condition; and a predictive assessment of future changes in SRWC due to changing climate scenarios.

2 Material and Methods

2.1 Description of Study Area

The study area is located in the central north region of the Punjab province, Pakistan, known by the name of SRWC. It is a 175 km thrust between the foot hills of Himalayan Mountains and Indus plains extending from *Jhelum* in the east and *Kala Bagh* in the west (Ali et al. 2011; Ahmad et al. 2008). Geographically, it is covering an area of 10,529 km^2 (Ahmad et al. 2008). The SRWC is constituted of five independent wetlands: i.e., Kallar Kahar Lake situated in *Chakwal* district; *Khabekki* Lake situated in *Khushab* district; *Ucchali*[4] Lake situated in *Khushab* district; *Jahlar* Lake situated in *Khushab* district; and *Namal* Lake situated in *Khushab* district (Fig. 1). These wetlands were notified as wetlands of international importance in 1976 and designated as wildlife sanctuaries and game reserves under 'Punjab Wildlife Act 1974 (Protection, preservation, conservation, and management)' (Arshad 2011).

The socioeconomic conditions of the area depict the population pressure along with the excessive use of natural resources for livelihood (Arshad 2011). Most of the people are serving in agriculture and Government sectors; however, industrial sector development is very low. Fields for agriculture purposes are very small in size and there is a trend of land ownership even if the land is not used for cultivation. The land around the lakes is privately owned, including the lake beds that can be used for cultivation. Wheat and different vegetables are the principal crops to grow. Lake water is used as irrigation water, while most of the communal grazing areas are badly eroded due to grazing pressure. Deforestation is common to meet the supply of wood to fuel markets and urban centers.

The lack of infrastructure development suggests that SRWC is badly affected by common household purposes and socioeconomic perspectives (Ali et al. 2011). The climate of the area is characterized by moderate summers and harsh winters. The wetlands of salt range are the source of water for domestic use and for irrigation (Ali and Akhtar, 2006; Ali et al. 2011). Entire Salt range is a hilly area comprised sandstone and limestone rocks, minerals like salt, coal, lime, and different kinds of clay and gypsum. Salt range vegetation is covered with coarse grasses, scrub plants, and subtropical dry evergreen scrub forests which vary with elevation, soil type, and precipitation (Ahmad et al. 2008). Major crops are wheat and lentils. The study area is well-known for breeding habitats of some threatened and vulnerable waterfowl

[4] *Ucchali*, *Jahlar* and *khabekki* lakes designated as a Wetlands Complex with International Importance under the *Ramsar* Convention along with eighteen other wetlands in Pakistan.

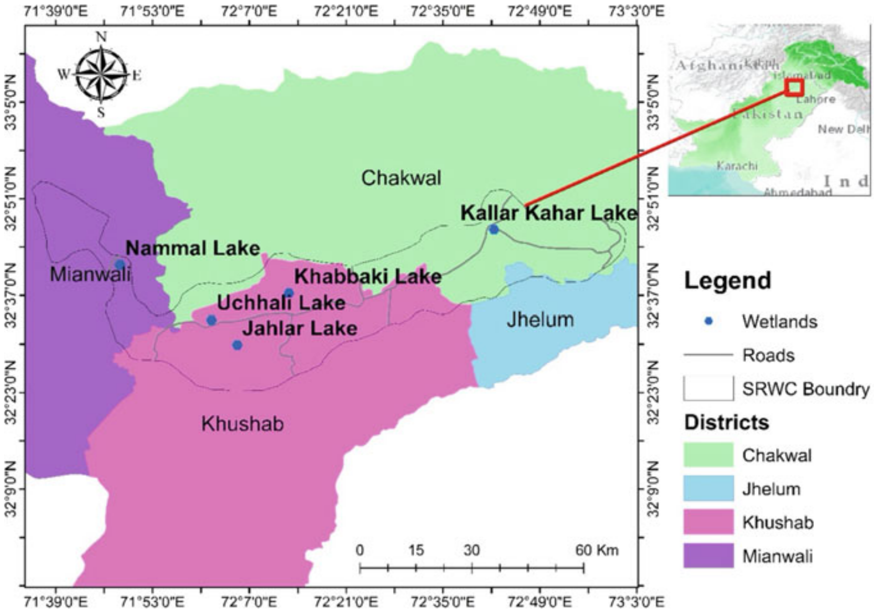


Fig. 1 Study area map showing SRWC

species, e.g., white-headed ducks and a core habitat for endemic Punjab Urial (Nawaz et al. 2012).

2.2 *Data Acquisition and Analysis*

Climatic Data

Climate Research Unit (CRU) data was acquired from Pakistan Metrological Department (PMD) for a period of 30 years from 1985 till 2014. Gridded climate dataset of CRU TS3.10 was constructed from monthly observations recorded at meteorological stations globally. Station anomalies were interpolated at 0.5-degree resolution grid cells covering all land surfaces, except Antarctica, and absolute monthly values were obtained by combining with the existing climatology (Harris et al. 2013). Area average of each CRU cell was used for the current study. Trend analysis was done for CRU acquired for monthly averages of precipitation (mm), temperature (°C), and potential evapotranspiration (mm).

Land Use Land Cover Change Detection

Change detection in LULC of SRWC was observed through Landsat 4–5 acquired on November 10, 1987, to November 21, 1991; ETM+ imageries acquired on November 5, 2000, and OLI8 imageries for November 20, 2014 (path/row 150/37). Annual change detection was done by using satellite data of the study area for which the images were pre-processed.

The images were first georeferenced and geometrically corrected and then co-registered normalized to remove geometric errors. The image processing was done on ERDAS-14 by using false color composites (Band combinations: 7, 5, 3 and 5, 4, 2) of the images. The change detection was observed through supervised classification for different time intervals between years 1987 till 2014. The years selected were 1987, 1991, 2000, and 2014 based on availability of data for the same season throughout the study time period (Fig. 2) which exhibited significant changes in LULC area (Table 1).

The classification is done for SRWC using maximum likelihood classification algorithm which is simple and easily implemented algorithm (Jonathan et al. 2007). For classification, six LULC classes, i.e., barren/uncultivated, scrub/grasses, water body, built-up area, forests, and croplands, were made. For maximum likelihood classification, training sites were made for all LULC classes by delineating an area of interest or polygon and, for each class 10, training samples were marked. Finally, the LULC map was generated.

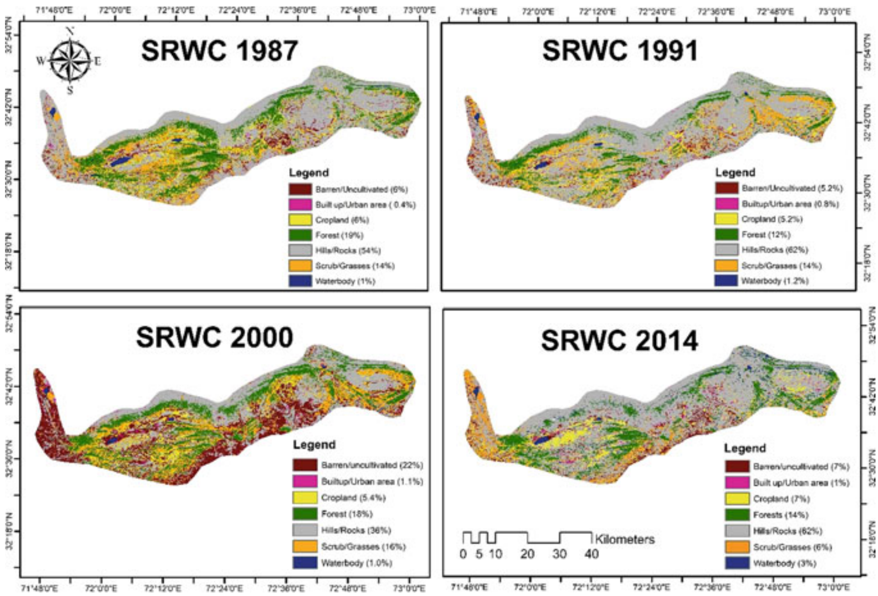


Fig. 2 Map showing SRWC LULC change in 1987, 1991, 2000, and 2014

Table 1 LULC change in SRWC

LULC classes	Total area of SRWC covered in hectares 1987	Total area of SRWC covered in percentage 1987	Total area of SRWC covered in hectares 1991	Total area of SRWC covered in percentage 1991	Total area of SRWC covered in hectares 2000	Total area of SRWC covered in percentage 2000	Total area of SRWC covered in hectares 2014	Total area of SRWC covered in percentage 2014
Barren/Uncultivated	12,707.85	6	11,398.05	5.2	48,135.86	22	14,413.85	7
Built-up/ Urban area	1039.60	0.4	1781.18	0.8	2484.19	1.1	2591.90	1
Cropland	13,554.92	6	11,646.58	5.2	11,920.95	5.4	15,760.07	7
Forests	41,113.32	19	26,231.71	12	39,993.06	18	30,551.77	14
Scrub/Grasses	30,324.26	14	30,910.41	14	35,133.29	16	13,843.60	6
Waterbody	2650.84	1.2	2542.50	1.2	2221.29	1.0	6569.65	3
Hills/Rocks	118,353.11	54	135,254.09	62	79,857.77	36	135,968.67	62

Accuracy Assessment for Image Classification

The accuracy assessment of the classified imageries was executed by generating series of reference points in ERDAS-14 (Butt et al. 2015). Post-processing classified the amount, location, and nature of change, and change detection maps were generated. Accuracy assessment of LULC classification of the years 1987, 1991, 2000, and 2014 was performed using 100 random samples. Based on reference points and LULC classes, matrix was generated.

Water Body Extraction Through Indexes

Indexes selected were Normalized Difference Vegetation Index (NDVI) (Eq. 1), and Normalized Difference Water Index (NDWI) (Eq. 2) for the extraction of wetlands vegetation and water body, respectively (Singh et al. 2016).

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}} \tag{1}$$

$$\mathrm{NDWI} = \frac{\mathrm{Green} - \mathrm{NIR}}{\mathrm{Green} + \mathrm{NIR}} \tag{2}$$

Threshold values were applied to the range of NDWI for delineating the surface water extent (Singh et al. 2016). Lake area for five wetlands in SRWC was calculated after threshold estimations by pixel counts using field calculator. Trend analysis demonstrated the response of wetland area change to climate change on yearly basis.

Predictive Assessment Through Scenario Data

Scenario-based approach was adopted by the Intergovernmental Panel on Climate Change (IPCC) in 2014 for future radiative forcing of climate change. Findings of the IPCC Fifth Assessment Report (AR5) were based on a new set of scenarios called Representative Concentration Pathways (RCPs). Scenarios selection, to identify and examine future climate impacts, is based on natural resources and their sensitivity to climate change (Daniels et al. 2012). Four sets of RCPs were adopted by the IPCC leading to global average radiative forcing of 2.6, 6.0, 4.5, and 8.5 W/m^2 by 2100. These scenarios were developed using assumptions related to future human activities, i.e., technology usage, economic growth, and land use in the absence of specific mitigation efforts or other relevant policies (Emanuel and Janetos 2013).

In current study, RCP 4.5 and RCP 8.5 scenario data was acquired from PMD to investigate the future impacts. RCP 4.5 represents an optimistic future pathway to stabilized radiative forcing of 4.5 w/m^2 with limited greenhouse gas emissions, while RCP 8.5 is a high emission scenario with radiative forcing of 8.5 w/m^2 with no policy changes to reduce greenhouse emissions. RCP data was generated from General

Circulation Model (GCM), i.e., Community Climate System Model (CCSM4) by using Linear Interpolation and Bias Correction (LIBC) statistical downscaling technique (Burhan et al. 2015). Decadal average rainfall values along with the temperature and potential evapotranspiration were arranged from 2010 to 2050 for both RCP 4.5 and RCP 8.5. Trend analysis predicted the future changes in SRWC.

3 Results and Discussion

3.1 Land Use Land Cover Change (LULC) Detection in SRWC

Results showed that during 1987, 6% of the total land area was barren/uncultivated while built-up/urban area was 0.4% and cropland was 6% of the total area (Fig. 2). Forests were 19% of the total area covering an area of 41,113 ha, scrubs/grasses cover 14.5% (30,324 ha), and 1.2% (2651 ha) was covered with water body. After four years when LULC was detected in the same area, a decline in barren land/uncultivated area was observed, i.e., 5.2% (11,398 ha) of total area.

Built-up area increased from 0.4 to 0.8% indicating sacrifice of barren land for population accommodation. Forest area was also reduced to 12% covering 26,232 ha of land in year 1991. There was less change in scrub/grasses and water body (Fig. 2). Later on, in 2000, a significant change in different LULC classes was observed. Barren land cover was 22% (48,136 ha). Consistent increase in built-up/urban area was observed which reaches to 1.1% in 2000. There was less significant change in croplands which remain to 5.4% in 2000. Forest area was retained back to 18% in 2000 covering an area of 39,993 ha. Scrub/grasses and water body area were same as in previous years (Fig. 2). During 2014, significant decrease in barren/uncultivated area was observed, which indicates either increase in population or agriculture practices in SRWC area (Meshesha et al., 2016; Dhas 2008). However, results have shown that built-up area has also decreased to 1% in 2014, which is attributed to initiatives for the protection of SRWC Ramsar sites in 2011. Although urbanization has been controlled to some extent, cropland and agriculture practices of the local people living there could not be controlled; this resulted in an increase of cropland area to 7% covering15760.07 ha of the total land area. Only 6% (13,844 ha) of the total area was covered with scrubs/grasses while total forest cover decreased to 14% (30,551 ha). An increase in the water body (i.e., 3%) was observed (Fig. 2). The overall classification accuracy of 1987 and 1991 LULC map was 83.33% while accuracy for 2000 land cover map was estimated at 79.17%. The total accuracy of LULC map of 2014 was 85.42%.

3.2 *Assessment of Change in Average Wetland Area Based on Climatic Conditions*

Trends in climatic conditions of five independent wetlands of SRWC showed fluctuations in rainfall, temperature, and potential evapotranspiration for a time series of 30 years (1985–2014). Change in wetland area has also been observed in this time period which is not similar for every lake in the SRWC.

The trend line for SRWC rainfall showed an increase from the year 1987 till 1995. This is in correlation with surface expansion also. Surface expansion means increase in the size of the area. As during these years, *Namal* Lake, *Jahlar* Lake, *Khabekki* Lake, and *Kallar Kahar* Lake showed an increase in surface area. *Namal* Lake showed an increase from 391.05 to 549.93 ha in 1992 while in 1993 an increase was observed in *Jahlar* Lake (from 20.34 to 21.93 ha), *Khabekki* Lake (from 262.44 to 275.88 ha), and *Kallar Kahar* Lake (from 2.52 to 136.14 ha) in correlation with the rainfall.

The significant change in the surface area of *Kallar Kahar* Lake was observed which increased from 2.5 ha in 1987 to 136 ha in 1993. In this time period, temperature records also correlated with the findings. The temperature showed a decrease till 1997 and started to increase till 2005. This was the time when decrease in rainfall was also observed that resulted in shrinkage of surface area of lakes. Surface area of *Namal* Lake decreased up to 197.32 ha while *Khabekki* Lake area reached to 94.04 ha in 2002. *Jahlar* Lake showed a decrease up to 9.36 ha in 2001, and *Kallar Kahar* Lake showed a decrease up to 89.79 ha in 2000. The most significant change was observed in *Ucchali* Lake whose area reduced to almost half (from 824.67 to 494.43 ha) from 1995 to 2001, which is in correlation with the increase of temperature during this time period (Fig. 3). It is continuously shrinking due to the prevalence of droughts in the area (Ali 2005). However, expansion in surface area of lakes has been observed in 2010 due to the increase in rainfall trends. The *Namal Lake* area expanded up to 752.26 ha in 2011. *Jahlar* Lake showed an increase up to 25.33 ha in 2012. The surface area of *Kallar Kahar* Lake and *Khabekki* Lake expansion was observed up to 214.7 ha in 2011, 164.47 ha, and 805.5 ha in 2014, respectively.

.

3.3 *Predictive Future Changes Using Climate Scenarios (RCP 4.5 and 8.5)*

Climate projections are useful for studying the future rate, magnitude, and direction of possible changes. Statistically downscaled future projections on rainfall, temperature, and potential evapotranspiration were used for the period 2010–2050 to assess the expected magnitude of climate response on wetlands as projected by CCSM4 model under RCP 4.5 and 8.5 (Fig. 4). Inter-annual variability in rainfall was observed under RCP 4.5 and 8.5. During 2011–2040, decrease in rainfall is expected and a

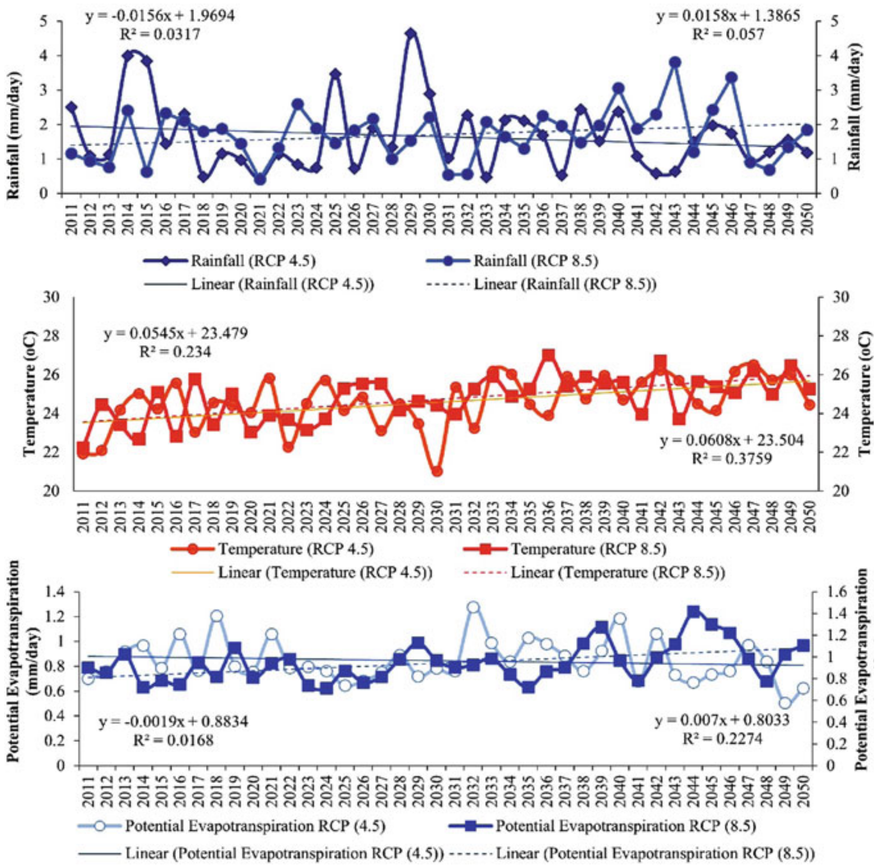


Fig. 3 Lake area change detection in relation to **a** rainfall **b** temperature and **c** potential evapotranspiration in SRWC

minimum rainfall up to 0.58 mm/day is likely to occur in 2041–2050 based on RCP 4.5 scenario (Fig. 4a), while temperature is expected to increase in corresponding years (Fig. 4b). During 2030–2041, decade maximum potential evapotranspiration is expected (Fig. 4c).

As for RCP 8.5, mean annual rainfall increases between 2011 and 2030, then decreases for 2031–2040, and then again increases (by small amount) for 2041–2050 (Fig. 4a), while mean annual temperature increases from 2011 till 2040 and then slightly decreases for 2041–2050 (Fig. 4b). Potential evapotranspiration showed an increase reaching a maximum of 1.4 mm during 2041–2050 based on RCP 8.5 (Fig. 4c).

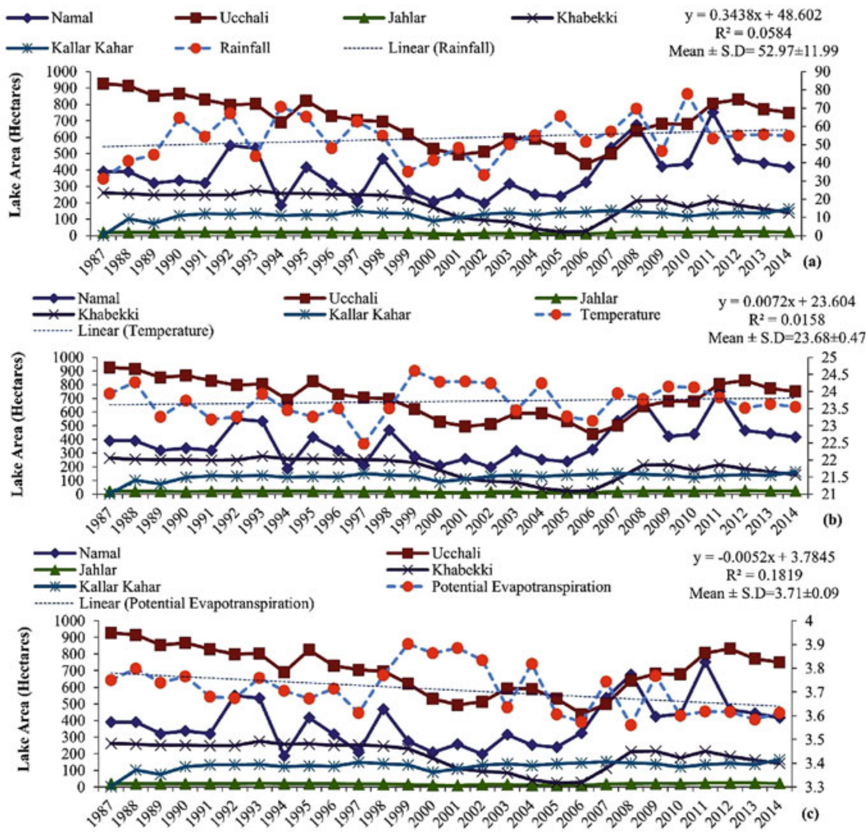


Fig. 4 Future impacts of climate change based on RCP 4.5 and RCP 8.5 in SRWC

Overall change detection accuracy of 85.42% indicated that maximum likelihood classification was an effective method for determining LULC changes. The individual image accuracies of 83.33% for 1987 and 1991, and 79.17% for 2000 and 85.42% for 2014 were effective in distinguishing wetlands sites and area from other land cover types.

The major change in LULC was observed in forest area from 1987 (41,113.32 ha) till 2014 (30,551.77 ha) (Table 1). The total decrease of 10,561.55 ha has been observed in 28 years due to increasing temperature and decreasing rainfall. *Kallar Kahar* wetland lies in *Chakwal* district. The decline in forest area of *Chakwal* district during the periods 2005–2006 and 2009–2010 has also been mentioned by Ahmad et al. (2010). The increase in settlement area from 0.4 to 1% of total covered area from 1987 till 2014 depicts the population growth that results in increasing the demand for natural resources, which are now at risk due to unsustainable utilization. Overgrazing, soil erosion, deforestation, and increased temperature in the area converted the green lush slopes into barren land that has increased from 6 to 7% of the total area.

Waterbody showed a decrease in the area from 1987–2000 while increase in total share from 1 to 3% was observed from 2000 to 2014. This is due to the decreasing and increasing rainfall trend in the area and past evidence of drop down of the water table from which not only the water bodies are severely affected, but also the vegetation of the area.

Mainly, reduction was observed in the area of *Ucchali* Lake up to 750 ha and *Khabekki* Lake up to 142 ha in 2014. However, *Namal*, *Jahlar*, and *Kallar Kahar* Lakes showed increase in volume. This change in lakes' volume proves the changes in temperature and rainfall patterns. The volume change depends on the amount of rainfall received that increases during monsoon season. Extreme climatic events like floods of 2010 and droughts of 2000 are also evident of such changes. According to IPCC (2007), surface warming and decrease in precipitation during past decades have contributed to drying trends of wetlands.

The expected temperature under RCP 4.5 and 8.5 scenarios indicated an overall warmer climate. This could be the start of a drying trend in wetlands ecosystems due to increased temperatures along with greater changes in precipitation and evaporation/evapotranspiration over a century. Maximum rainfall is expected with increase in temperature and potential evapotranspiration between 2021 and 2030, while in 2031–2040 rainfall trend showed a decrease with expected minimum fluctuations; however, maximum increase in temperature and minimum fluctuations with increase in potential evapotranspiration is expected. During 2041–2050, maximum potential evapotranspiration is expected based on RCP 8.5, while it is expected to decrease based on RCP 4.5 from past decades. Minimum rainfall and maximum temperature are likely to occur in 2041–2050. In order to meet SDGs, the National Framework for SDGs has been submitted in 2018 to National Economic Council. Managing and conserving wetland are mentioned in the national priority Target 6.6 and Target 15.1 of the Framework (Planning Commission of Pakistan 2018).

In terms of sustainability, the importance of protection and conservation of wetlands has been accepted globally. The severity of threats to the most diverse ecosystem, their reliability, and veracity are internationally acknowledged. Presently, the Pakistan Wetland Program is functioning to conserve, promote, and protect the biodiversity of the country which has great global significance. The major elements for an effective conservation of natural wetlands at local level consist in creating and maintaining a sustainable environment and implementing the wetland conservation strategy at four major sites, including SRWC, to present them as model wetland sites. In this perspective, the WWF Pakistan wetland projects are focusing on the identification and conservation of wetlands, enhancing biodiversity, creating awareness among the public, and developing a strategy for the sustainable management of wetlands in Pakistan. With all such efforts, the public and local people are still unaware of the value of this natural ecosystem; therefore, further planning and efforts are required in this regard. Accordingly, in light of this study findings, below are some reliable recommendations that can be adopted by interested stakeholders in order to develop solutions relating to the protection of wetlands face to climate change:

- Increasing awareness among local community can play its vital role in reducing the damages to wetlands.
- Involvement of stakeholders at provincial level can improve the collaborative management of the natural resources.
- Alternative livelihood opportunities (i.e., ecotourism and skills development) should be provided for local communities in order to alleviate poverty and over-exploitation of resources.
- Enforcement and implementation of rules, regulations, policies, and management plans should be promoted for wetlands protection and preservation.
- Catchment area of *Uchhali* Lake, *Khabikki* Lake, *Jahlar* Lake, *Kallar Kahar* Lake, and *Namal* lake should be protected by proper planning and development of defined boundary in the natural area.
- Environmental impact assessment should be conducted in the area before executing any development project.
- Water quality monitoring and management plans should be developed and implemented.
- Studies regarding the climate impacts on wetlands should be promoted to determine the wetlands responses.
- Policy makers and researchers should take appropriate measures for wetland restoration before it goes under a complete or irreversible change due to extreme climate events.

4 Conclusion

It is concluded that significant LULC changes were evident by decline in scrub/grass vegetation and forest area (6% and 14%, respectively) and increase in the area covered by cropland (7%), settlements (1%), and barren/uncultivated land (7%). The overall increase in the water body was observed up to 3% of the total area. Climate changes were also observed during 1985–2014. Changes in lakes surface area due to climate change were evident by increase in the surface area of lakes when rainfall is observed at its maximum. Moreover, temperature rise resulted in surface area shrinkage. Future climatic predictions have resulted in the hydrological alteration due to disturbances in climate patterns and drying trend is expected to be encountered by these wetlands.

Wetlands of salt range showed different fluctuations in the surface water in accordance with inter-annual variations in climatic parameters like precipitation, temperature, and potential evapotranspiration. Increase in rainfall pattern has direct correlation with increase in surface area. Climate change and wetland studies are underway to determine the impacts, relationship, and the responses worldwide while a limited literature is available in Pakistan regarding wetland changes due to climate change. The Salt Range has an environmental significance in addition to being prone to extreme climate events like droughts and floods. Prevailing water shortage conditions in the area also drive the attention toward the protection of these wetlands. Scientific research over a longer time is needed, specifically in connection with wetlands and climate change in SRWC. The present study determined the relationship between climate variables and wetlands that drive the attention of policy makers, environmentalists, management plan developers, and local communities to protect, conserve, and manage these wetlands complex in terms of achieving sustainability at higher priority.

Acknowledgements The authors are grateful to Pakistan Meteorological Department (PMD), Research and Development Division of Pakistan for their cooperation in providing climatic data and guidance during the conduct of this research.

References

Ahmad I, Hussain M, Ahmad MS, Hameed M (2008) Spatio-temporal effects on association of plant species in soone valley of Pakistan. Pak J Bot 40(5):1865–1876

Ahmad SS, Sherazi A, Shah MT (2010) A preliminary study on climate change causing decline in forest cover area in District Chakwal, Pakistan. Pak J Bot 42(6):3967–70

Ali Z (2005) Ecology, distribution and conservation of migratory birds at Uchalli Wetlands Complex, Punjab, Pakistan. Doctoral dissertation, University of the Punjab, Lahore

Ali Z, Akhtar M (2006) Decreases in size of lakes and numbers of birds in selected wetlands in Pakistan. Waterbirds around the world. The Stationery Office, Edinburgh, UK, pp 294–295

Ali Z, Shelly SY, Bib F, Joshua G, Khan AM, Khan BN, Akhtar M (2011) Salt range wetlands complex, exploratory/baseline survey. J Anim Plant Sci 21(2):1018–7081

Arshad M (2011) Site management plan: Kallar Kahar game reserve. In: A part of Salt Range Wetlands Complex. Pakistan Wetlands Programme, WWF-Pakistan

Burhan A, Waheed I, Syed AA, Rasul G, Shreshtha AB, Shea JM (2015) Generation of high-resolution gridded climate fields for the upper Indus River Basin by downscaling CMIP5 outputs. J Earth Sci Climatic Change 6(2):1

Butt A, Shabbir R, Ahmad SS, Aziz N, Nawaz M, Shah MT (2015) Land cover classification and change detection analysis of Rawal watershed using remote sensing data. J Biodivers Environ Sci 6(1):236–248

Daniels AE, Morrison JF, Joyce LA, Crookston NL, Chen SC, Et McNulty SG (2012) Climate projections FAQ. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station

Desta H, Lemma B, Fetene A (2012) Aspects of climate change and its associated impacts on wetland ecosystem functions: a review. J Am Sci 8(10):582–596

Dhas AC (2008) Population pressures and land use changes in Southeast Asian countries: recent evidences

Emanuel WR, Janetos AC (2013) Implications of representative concentration pathway 4.5 methane emissions to stabilize radiative forcing. Pacific Northwest National Lab.(PNNL), Richland, WA (United States)

Gitau PN, Ndiritu GG, Gichuki NN (2019) Ecological, recreational and educational potential of a small artificial wetland in an urban environment. Afr J Aquat Sci 44(4):329–338

Harris IP, Jones PD, Osborn TJ, Lister DH (2013) Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 dataset. Int J Climatol 34(3):623–642

Hossain MS, Hein L, Rip FI, Dearing JA (2015) Integrating ecosystem services and climate change responses in coastal wetlands development plans for Bangladesh. Mitig Adapt Strat Glob Change 20(2):241–261

Hussain M (2002) Exploration of legume diversity endemic to salt range in the Punjab. Annual technical report submitted to University of Agriculture, Faisalabad, Pakistan

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change, 1–976

Izhar-uI-Haq ED, Iqbal JZ (2016) Environmental conservation of wetlands in Pakistan. Pakistan Engineering Congress

James A, Binny RN, Lee WG, Payne J, Stringer N, Holland EP (2019) Predicting water levels in ephemeral wetlands under climate change scenarios. Thyroid Res 12(4):427–435

Jaramillo F, Desormeaux A, Hedlund J, Jawitz JW, Clerici N, Piemontese L et al (2019) Priorities and interactions of sustainable development goals (SDGs) with focus on wetlands. Water 11(3):619

Jeffries MJ, Epele LB, Studinski JM, Vad CF (2016) Invertebrates in temporary wetland ponds of the temperate biomes. In: Invertebrates in freshwater wetlands. Springer, Cham, pp 105–139

Jonathan M, Meirelles MS, Berroir JP, Herlin I (2007) Regional scale land use/land cover classification using temporal series of modis data MS/MT. Rev Bras Cartogr 59:1–7

Junk WJ, An S, Finlayson CM, Gopal B, Květ J, Mitchell SA et al (2013) Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. Aquat Sci 75(1):151–167

Khan AA, Arshad S (2014) Wetlands of Pakistan: distribution, degradation and management. Pak Geogr Rev 69(1):28–45

Meshesha TW, Tripathi SK, Khare D (2016) Analyses of land use and land cover change dynamics using GIS and remote sensing during 1984 and 2015 in the Beressa Watershed Northern Central Highland of Ethiopia. Model Earth Syst Environ 2(4):1–12

Nawaz T, Hameed M, Ashraf M, Ahmad F, Ahmad MS, Hussain M, Ahmad I, Younis A, Ahmad KS (2012) Diversity and conservation status of economically important flora of the Salt Range, Pakistan. Pak J Bot 44:203–211

Nazir F, Malik I, Shah SA (2018) Census study of ducks, swans and geese from high-altitude wetlands of Pakistan. J Bioresour Manag 5(4):4

Okuno E, Gardner RC, Archabal M, Murphy K, Willis J (2017) Bibliography of 2016 Scientific Publications on the Ramsar Convention or Ramsar Sites. Available at SSRN 3063547

Osborn D, Cutter A, Ullah F (2015) Universal sustainable development goals. Understanding the Transformational Challenge for Developed Countries

Planning Commission (2018) Summary for the National Economic Council (NEC), Sustainable Development Goals (SDGS) National Framework, Government of Pakistan. Available at https://www.pc.gov.pk/

Qamer FM, Ashraf MS, Hussain N, Saleem R, Ali H, Mirza H, Akram U, Raza SM (2009) Pakistan wetlands GIS-A multi-scale national wetlands inventory. In: 33rd international symposium on remote sensing of environment

Qazi F, Ahmad SS, Aziz N (2012) Change analysis of wetlands for the year 1971–2008 of Kallar Kahar, Punjab, Pakistan: case study. J Int Environ Appl Sci 7(1):140

Rais M, Anwar M, Mehmood T, Hussain I (2011) Bird diversity and conservation at KallarKahar Lake with special reference to water birds. Pakistan J Zool 43(4):673–681

Salma S, Shah MA, Rehman S (2012) Rainfall trends in different climate zones of Pakistan. Pak J Meteorol 9(17)

Sanjerehei MM, Rundel PW (2017) The future of Iranian wetlands under climate change. Wetlands Ecol Manage 25(3):257–273

Seifollahi-Aghmiuni S, Nockrach M, Kalantari Z (2019) The potential of wetlands in achieving the sustainable development goals of the 2030 agenda. Water 11(3):609

Singh M, Mohapatra SN, Sharma M (2016) Normalised difference water index-based water surface area delineation and assessment. Int J Environ Sci 6(5):634–645

Taillardat P. Thompson BS, Garneau M, Friess D (2019) Are wetlands a threat or an affordable solution for climate change mitigation? AGUFM, 2019, PA33E-1129
Varghese S, Narayanan SP, Raj VP, Prasad VH, Prasad SN (2008) Analyses of wetland habitat changes and its impacts on avifauna in select districts of the indo-Gangetic plains of Uttar Pradesh, India, between 1972 and 2004. In: Proceedings of Taal 2007: the 12th world lake conference

Dr. Syeda Maria Ali is an Assistant Professor at the Department of Environmental Science, Faculty of Basic and Applied Sciences, International Islamic University, Islamabad, Pakistan since September 2009. Her areas of interests are ecology, GIS and RS, water quality and vegetation science. In addition to teaching, Dr Ali is engaged in research areas, including climate change scenarios, vegetation and soil science, and urban ecology.

Ms. Sehrish Aslam has a Master degree in Environmental sciences from Department of Environmental Sciences, Faculty of Basic and Applied Sciences, International Islamic University, Islamabad, Pakistan. Her areas of interests are wetland management and climate change.

Ms. Aneeza Islam has a Master Degree in Environmental Sciences and is currently pursuing her Ph.D. in Environmental Sciences at the Faculty of Basic and Applied Sciences, International Islamic University, Islamabad. Her areas of interests cover urban management and climate change.

Dr. Muhammad Afzaal is the Director of the Pakistan Meteorological Department (PMD), Islamabad, Pakistan. He has a Ph.D. degree in Meteorology from Beijing, China. His area of specialization is climate dynamics.

Bioresource Nutrient Recycling and Its Relationship with Soil Health Under Irrigated Agro-ecosystems

Saba Nazir, Qamar uz Zaman, Abdulrasoul Al-Omran, Jan W. Hopmans, Kamran Ashraf, Nayab Komal, and Mirza Barjees Baig

Abstract Soil health is presented as an integrative property that reflects the capacity of soil to respond to agricultural intervention, so that it continues to support both the agricultural production and the provision of other ecosystem services. The important challenge within sustainable soil management is to conserve ecosystem service delivery while optimizing agricultural yields. The low fertilizer use efficiency in most of the fertile soils is another factor adding in more use of chemical fertilizers. Intensive land use with continuous and injudicious use of higher doses of inorganic fertilizers significantly influences soil health and crop growth. Chemical fertilizers affect soil properties both positively and negatively. Due to the scarcity of mineral (Nitrogen, Phosphorous, and Potassium) and soil resources and food insecurity, the recycling

S. Nazir · Q. uz Zaman (✉) · N. Komal
Department of Environmental Sciences, The University of Lahore, Lahore, Pakistan
e-mail: qmar.zaman1@envs.uol.edu.pk

S. Nazir
e-mail: sabawarraich989@gmail.com

N. Komal
e-mail: nayabkomal5@gmail.com

A. Al-Omran
Department of Soil Science, King Saud University, Riyadh, Saudi Arabia
e-mail: rasoul@ksu.edu.sa

J. W. Hopmans
Soil Science and Irrigation Water Management, University of California, Davis, Davis, USA
e-mail: jwhopmans@ucdavis.edu

K. Ashraf
Department of Food Sciences, Government College University, Faisalabad, Sahiwal Campus, Pakistan
e-mail: kamran2417@gmail.com

M. B. Baig
Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, Riad, Saudi Arabia
e-mail: mbbaig@ksu.edu.sa

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_23

and recovery of resources should be at the center of future efforts. Bioresources management is a well-known and widely accepted practice as a key component of conservation agriculture. Moreover, improper management (intensive agriculture, residues burning, and improper crop rotation) of these bioresources (organic amendments, green manuring, and crop residues management) often limits their beneficial effects. In this chapter, we reviewed all recent findings to understand and summarize the different aspects of the bioresource management and recycling and their impact on soil health in farming systems, which are linked to the environment and ecology.

Keywords Bioresources · Chemical fertilizers · Crop residues · Soil health · Soil quality

1 Introduction

The growing demand for food in developing countries has led to tremendous increase in food production around the world. Hence, agro-based activities represent profitable businesses, both in developing as well as developed countries (Liu et al. 2021). Large stretches of wasteland have been converted to arable lands due to developments in water management systems, modern agro-technologies (robots, temperature and moisture sensors, aerial images, and GPS technology), and large-scale agrochemical deployment (Maiti et al. 2021). These measures have resulted in global environmental pollution and increased complexity in the disposal of agricultural wastes (Srinivasarao et al. 2013; Wang et al. 2021; Iqbal et al. 2021a, b).

Soil health is an ancient and ubiquitous concept. The protection of soil health was written into Greek and Roman treatises on agricultural productivity over 2000 years ago (Karlen 2012; Nawaz and Farooq 2021). It is defined as the capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans (NRCS 2012). Although often used synonymously with 'soil quality,' soil health differentiates itself from soil quality because of its focus on biological attributes (Karlen 2012). Indeed, the use of the term 'health' suggests a universal paradigm shift in our scientific understanding of soils. The soil ecosystem is now seen and discussed as a living organism (NRCS 2012; Nawaz and Farooq 2021).

There is no way for us to meet the growing demands for food, feed, fiber, and fuel if we do not maintain soil health (Sanchez 2002; Shafer et al. 2021). Soil health depletion can often be self-reinforcing as low-quality soils produce low-quality biomass, which, in turn, results in low-quality manure. The low-quality manure immobilizes nutrients such as phosphorous in the soil and thus perpetuates a cycle that reduces soil health. Breaking this cycle will be a critical step in improving food security regionally and across the globe; improving and protecting soil health will be a serious step in meeting the food demands of the next century (Lal et al. 2021) (Fig. 1).

Chemical fertilizers not only improve crop production by supplying more nutrients in the soil for plant uptake, but it also affects the soil physical, chemical, and biological properties both positively and negatively as mentioned in (Fig. 2) (Zaman et al. 2019).

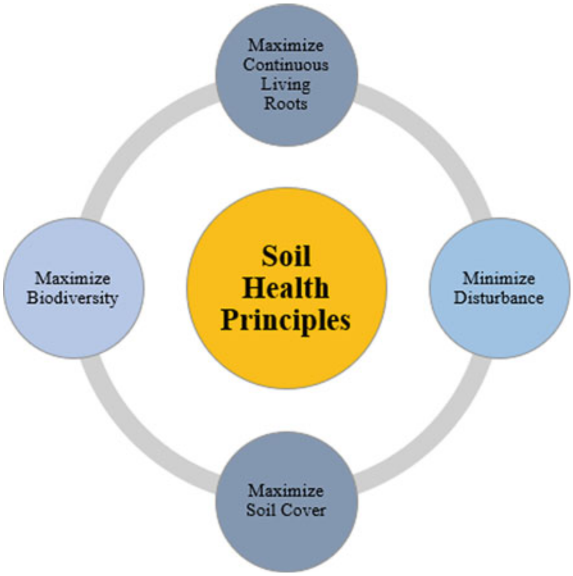


Fig. 1 Principles of soil health. *Source* Riaz et al. (2020)

These soil properties combined maintain soil health and improve crop growth and can be evaluated by soil quality (Shukla et al. 2006; Mendes et al. 2021). Soil physical properties—such as texture, compaction, infiltration rate, seepage, hydraulic conductivity, soil porosity, and bulk density—soil chemical properties, nutrients status, cation exchange capacity, electrical conductivity, pH, and soil microbial community change with long-term and intensive application of chemical fertilizers (Riaz et al. 2020).

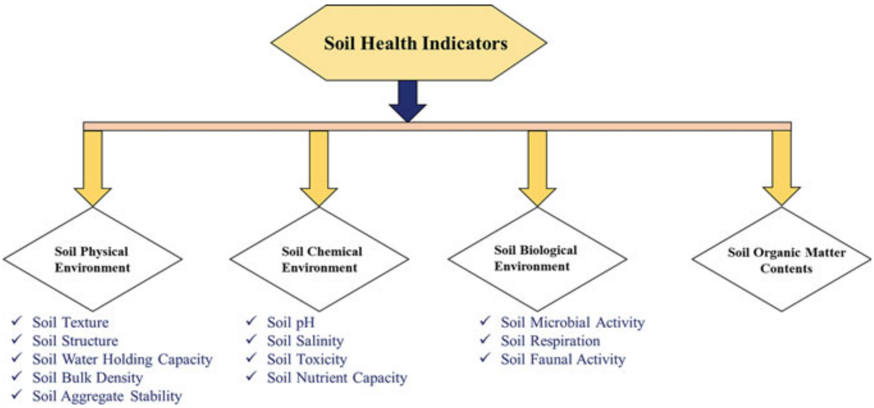


Fig. 2 Soil health in relation to physio-bio-chemical environment. *Source* Amelung et al. (2020)

Crop residue management is a well-known and widely accepted practice for controlling various soil physical, chemical, and biological functions (soil bacterial communities and arbuscular mycorrhizal fungi). The maintenance of crop residue cover on the soil surface benefits belowground food webs and processes, and improves the abundance and diversity of soil bacterial communities, including beneficial microbes like *Pseudomonas, Burkholderiales*, and *Rhizobiales* (Ceja-Navarro et al. 2010; Xia et al. 2019) with plant growth promoting capacity and arbuscular mycorrhizal fungi, with beneficial effects on crop yield and biocontrol (Guerrieri et al. 2020). Crop residues incorporate a large number of nutrients in the soil for crop production and affect soil water movement, runoff, and infiltration. In a conservation agriculture (CA) system, the successful management of crop residues is an integral part of it (Jat et al. 2019). However, the decomposition of crop residues has both positive and negative impacts on crop production (Lu 2020). The negative effects of allelochemicals from crop residues on crop growth can be adjusted by crop residue returning management (Fu et al. 2021). Soil management with crop residues covers a wide range of aspects, like residue decomposition, soil erosion control, nutrient recycling and availability to plants, control of weed pests, and various conservation practices related to tillage for maximizing crop yields (Liu et al. 2020). It is reported that soil, air, and water, which have marvelous interaction with plants, release various essential inorganic nutrient elements for plant growth (Meena and Lal 2018; Zhao et al. 2020). The plant availability of NPK nutrients from crop residues mostly depends on different soil physical, chemical, and biological processes (Lal 2005; Rathod et al. 2019).

The use of farmyard manure (FYM) alone as a substitute to inorganic fertilizer is not enough to maintain the present levels of crop productivity of high yielding varieties (Efthimiadou et al. 2010). Therefore, the integrated nutrient management in which both organic manures and inorganic fertilizers are used simultaneously is the most effective method to maintain a healthy and sustainably productive soil. Emerging evidence indicated that integrated soil fertility management involving the judicious use of combined organic and inorganic resources is a practicable approach to overcome soil fertility constraints (Dejene and Lemlem 2012; Mugwe and Otieno 2021).

In the modern days of agricultural science, crop rotation and green manuring (GM) offer a technology to achieve sustainable production efficiently. One of the options to maintain sustainability in agriculture by restoring soil quality (especially in tropical soils) and reclaiming degraded soil is to increase soil OM content by GM (Kumar et al. 2014a, b; Chimouriya et al. 2018), because this practice is eco-friendly, non-polluting, and non-degrading to soil, water, and air (Yang et al. 2018). Moreover, like chemical fertilizers, GM does not exhibit any adverse effect on food commodities. GM with high nutrient concentrations and low C/N ratios largely increases their value as organic fertilizer in crop production (Talgre et al. 2012; Martín-Lammerding et al. 2021). The use of GM together with adequate residue management and crop rotation can conserve or increase soil fertility, promote nutrient cycling at farm scale, bring crop nutrients up from lower soil profiles, smother weeds and prevent weed seedling growth, and reduce the external nutrient inputs (Melero et al. 2006; Yadav et al. 2019).

Mostly, farmers in developing countries focus on chemical-based agriculture through the misuse of chemical-based fertilizers, the burning of crop residues, and the limited use of organic amendments, thereby severely affecting soil health. In many rural areas of Punjab, the intensive crop production, combined with removal and burning of crop residues, has depleted agricultural soils, jeopardizing their productive capacity and ability to meet the needs of future generations. Holistic production management systems which promote and enhance agro-ecosystem health that are socially, ecologically, and economically sustainable are necessary in order to protect our soils while maintaining high productive capacities. Thus, the present effort is focused on developing a better understanding of cutting-edge, low-cost, and eco-friendly nutrient-management technologies that involve the recycling of locally available bioresources and the intensive use of biochar for carbon sequestration to sustain crop productivity and soil health in intensive agricultural systems of Pakistan.

2 Indicators of Soil Quality and Soil Health

The success of management in keeping soil quality depends on our understanding of how soil responds to agricultural use and practices over time. Therefore, methods to quantify soil quality must assess changes in selected soil attributes over time. However, the soil quality cannot be measured directly from the soil alone, but it is inferred from soil properties and behavior under defined conditions (Amelung et al. 2020).

Furthermore, there is no single measurement that quantifies the soil quality. Soil quality depends on a large number of chemicals, physical, and biological properties, and its characterization requires the selection of properties most sensitive to changes in management practices such as intercultural practices, intensive plowing, and residue burning (Gałązka et al. 2020). Good indicators of soil quality must be related to ecosystem processes, integrating physical, chemical, and biological properties. Initially, the use of a basic set of indicators to assess soil quality in numerous agricultural management systems was proposed (Bongiorno et al. 2019).

However, the use of simple soil quality indicators, which have meaning to farmers and other land managers, will likely be the most fruitful means of linking science with practice in assessing the sustainability of management practices. As such, the assessment of soil quality, and within their time trends, is a primary indicator of sustainable management (Doran 2002; De Deyn and Kooistra 2021). To assess the soil quality, indicators (soil properties) are usually linked to a specific soil function—e.g., as a medium for plant growth—and reflect changes over various spatial and temporal scales (Gray and Morant 2003). Best soil quality indicators are those selected soil properties that are sensitive, easy to measure, verifiable, and well related to land

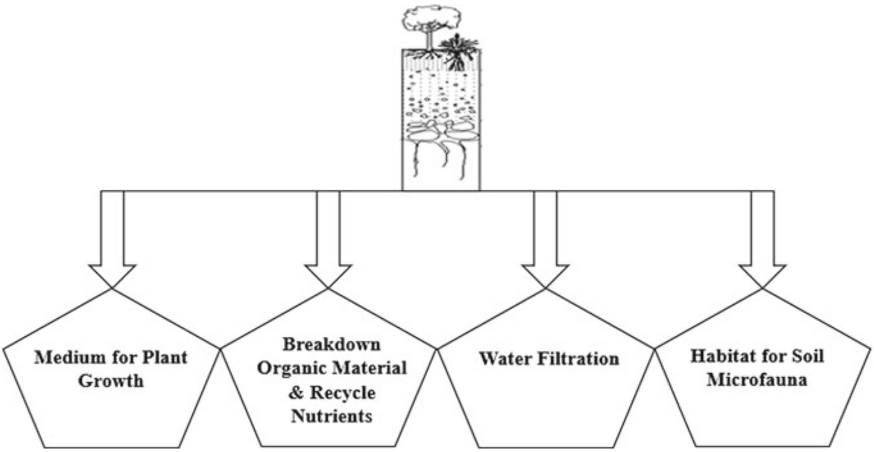


Fig. 3 Pictorial view of soil ecosystem. *Source* Erkossa et al. (2007)

management and environmental transformation (Erkossa et al. 2007; Velmourougane and Blaise 2017) (Fig. 3).

2.1 Physical Indicators

Bulk density, water retention, flow parameters, and structural stability were chosen as basic physical soil characteristics. The effects of irrigation are also analyzed.

The soil bulk density (and porosity) varies according to the soil texture, structure, and organic matter content, but within a given soil type, it can be used to monitor the degree of soil compaction and puddling. Changes in bulk density affect other properties and processes that influence water and oxygen supply (Schoenholtz et al. 2000; Velmourougane and Blaise 2017). Water soil and flow parameters are universally important for monitoring all soil functions. The available water holding capacity and saturated hydraulic conductivity are the two most frequently found in minimum data set (MDS) of physical soil quality indicators. The available water holding capacity measures the relative capacity of a soil to supply water, and the saturated hydraulic conductivity is an indicator of both drainage rate and aeration (Schoenholtz et al. 2000). The aggregate stability describes the ability of the soil to retain its arrangement of solid and void space when exposed to different stresses. The structural stability of soil is an essential parameter, influencing many soils physical properties such as water infiltration and water–air ratio, but also erodibility, biological activity, and plant growth (Six et al. 2000). The soil structure as such is not a plant-growth factor directly, but it influences practically all plant-growth factors. Specifically, it determines the depth that roots can penetrate, the amount of water that can be stored in the soil (soil water distribution, movement, and retention), the availability of plant nutrients (nutrient recycling), aeration, movement of soil fauna, and microbial activity (Schloter et al. 2006).

Stability characteristics are generally specific for a structural form and the type of stress being applied. A measure of aggregate stability could serve as a surrogate for soil structure, which is critical for root system development (Velmourougane and Blaise 2017). To evaluate the impact of management practices on the soil environment, it is necessary to quantify changes in soil structure. Since crop management systems generally have a strong influence on soil structural characteristics, the aggregate stability is considered a key indicator to assess soil structure and soil quality. The decline in soil structure is increasingly seen as a form of soil degradation and is often related to land use and soil/crop management practices such as timely sowing of crop, proper seeding depth and timely irrigation, fertilizer, and plant protection measures (Chan et al. 2003). For improving the productivity of soil under semi-arid and arid region, it is fundamental to understand the behavior of hydro-physical properties and how to modify soil structure and pore size distribution for improving crop growth and water-use efficiency (WUE).

Improving soil physical properties, such as bulk density, soil texture, water holding capacity, total porosity, hydraulic conductivity, water stable aggregates, and water availability for crops are considered the main factors influencing its ability to supply water, air, heat, and dissolved nutrients for crops. Biochar might be able to change the hydro-physical attributes of agricultural soils, positively. The application of biochar to sandy loam soils improved pore size distribution because the largest pores (macro pores) changed to meso and micro pores due to mix biochar materials with soil, compared with control/un-amended soil (Dokoohaki et al. 2017) and enhanced size and number of soil pores. Several researchers have reported that compost and superabsorbent polymers (SAPs), also known as soil polymers or macromolecular polymers, are capable of repeatedly absorbing, retaining, and releasing extremely large amounts of water relative to their own weight. Thus, they can improve water conservation in soils, prevent deep percolation and soil nutrient loss, and maximize the efficient use of water and fertilizer (Alkhasha and Al-Omran 2020; Al-Omran et al. 2021).

2.2 Chemical Indicators

Among the chemical indicators of soil quality, the soil reaction (pH) is extremely important. This basic factor is known to influence nutrient availability and microbiological activity. Soil organic matter (SOM) is one of the most significant parameters of soil quality for both scientists and farmers (Bhaduri et al. 2020). Soil organic matter is both a nutrient sink and source, enhances soil physical and chemical properties, and promotes biological activity. It is well known that cultivation of the natural land resources induces SOM losses which, in turn, directly affects the soil chemical, physical, and biological properties, and results in loss of production potential of crops. Soil organic carbon and total nitrogen are arguably the most significant single indicators of soil quality and productivity (Enya 2019).

2.3 Microbiological Indicators

SOM levels may vary across years, whereas active SOM-fractions like macro- and light fraction-organic matter, soil microbial biomass, and microbial functions may change within shorter periods of time (Smith et al. 2000). Soil microorganisms have been shown to be potentially useful (early and sensitive) indicators of soil health, because they respond to soil management in time scales (month/years) that are relevant to land management. Soil micro biota, existing in extremely high density and diversity, rapidly modify the energetic performance and activity rates to changing environmental conditions (Schloter et al. 2003; Lindsay et al. 2020). Other biological measurements, such as enzymatic activities (alkaline phosphatase, soil dehydrogenase, soil urease, etc.), are not very useful measures of soil quality because they are too much affected by both seasonal and spatial variations. The national programs for monitoring soil quality are generally based on microbial biomass and soil respiration measurements and may include nitrogen mineralization, microbial diversity, and functional soil fauna group measurements (Thiele-Bruhn et al. 2020). Soil microbial biomass can be defined as organisms living in soils that are generally smaller than approximately 10 μm. Most attention is given to fungi and bacteria, and they are generally dominating within the biomass (Coonan et al. 2020). It has been suggested that the microbial biomass content is an integrative signal of the microbial significance in soils because it is one of the few fractions in soil organic matter that is biologically meaningful, sensitive to management or pollution, and it can be easily measured (Ronchi et al. 2019).

Soil microbial respiration, measured through carbon dioxide production, is a direct indicator of microbial activity and indirectly reflects the bio-availability of organic matter (Gómez et al. 2006; Velmourougane and Blaise 2017). The soil microbial activity leads to the liberation of nutrients available for plants but also to the mineralization or mobilization of pollutants and xenobiotics. Thus, the microbial activity is of crucial importance in biogeochemical cycling. Microbial activities are mostly regulated by nutritional conditions, temperature, water availability, pH, and oxygen supply (Schloter et al. 2003; Ronchi et al. 2019).

3 Agricultural Practices and Their Impact on Soil Quality

Soils are under pressure globally, and their quality is decreasing. The European Commission (2002) recognized soil degradation in Europe as a serious problem. It is driven by human activities such as by inappropriate agricultural practices, urban and industrial sprawl, industrial activities, construction, and tourism. The alteration of soil characteristics by anthropogenic impacts (intensive farming and residues burning) changes the functional capacities of the soil (Tóth 2008) (Fig. 4).

Agricultural technologies and current practices like monocropping, residue management, mineral fertilization, overuse of pesticides, heavy agricultural machinery, inadequate management practices of soil and irrigation can significantly affect the soil quality by changing its physical, chemical, and biological properties (Ronchi et al. 2019) (Fig. 5).

The long-term human impact (e.g., sealing), as well as short-term soil management (e.g., irrigation), modifies material and energy flows. Erosion, declines in organic matter content and biodiversity, contamination, sealing, compaction, salinization, and landslides were identified as the main soil threats (Andrews and Carroll 2002; European Commission 2002; Ronchi et al. 2019). The conventional horticultural cropping, due to continuous soil removal and intensive use of pesticides and fertilizers, is the main activity leading to the deterioration of soil physical, chemical, and biological properties (Albiach et al. 2000). It is important to be aware that the soil is a finite and non-renewable resource, because its regeneration through chemical and biological weathering of underlying rock requires a geological time (Huber et al. 2001; Velmourougane and Blaise 2017).

Preliminary mechanical interventions on soils, such as terracing, land leveling, and deep plowing, change soil profiles from their natural form to anthropogenic. These changes lead to major landscape modifications and land degradation (Borselli et al. 2006). In addition, alternative land management techniques toward more intensive agricultural production cause the abandonment of traditional practices (Zalidis

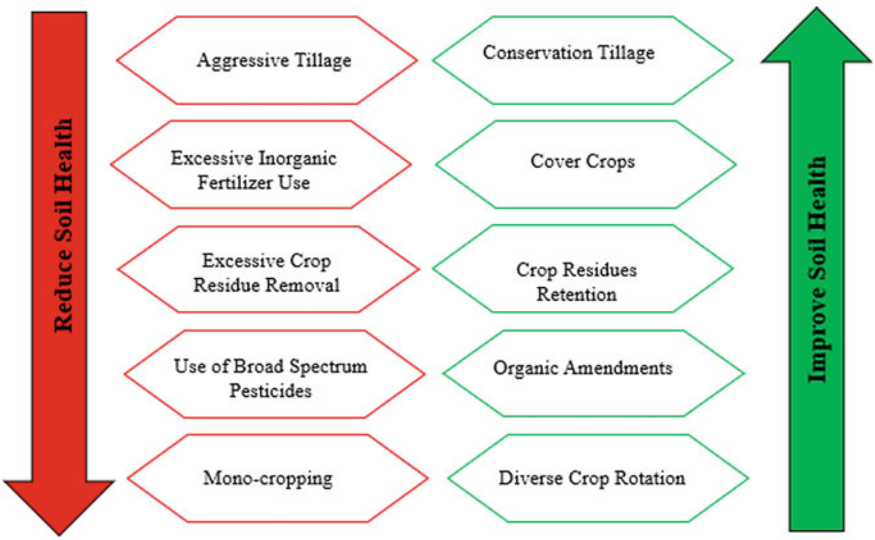


Fig. 4 Agricultural practices and soil health. *Source* Ronchi et al. (2019)

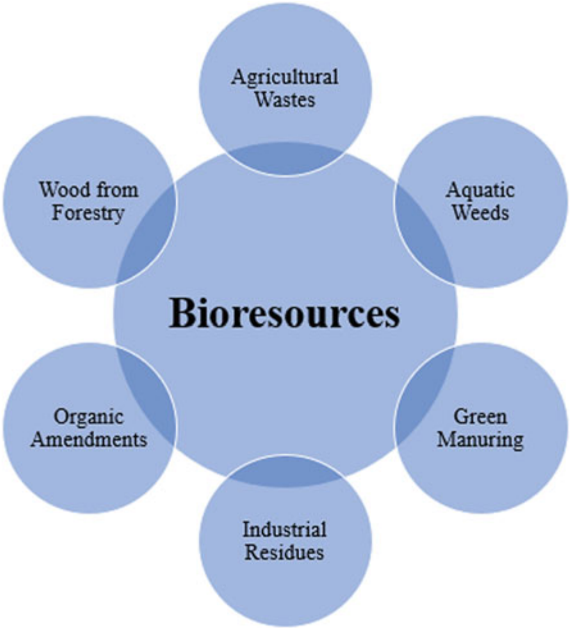


Fig. 5 Common bioresources used for improving soil health in Pakistan. *Source* Nazir et al. (2021)

et al. 2002; Ronchi et al. 2019). Heavy machines such as bulldozers are being used for large-scale soil movements in order to create new terracing systems for vineyards and orchards. These movements are not necessarily lawful or done by a technical expertise (Malet et al. 2003), thus causing land degradation by erosion (Lundekvam et al. 2003) and landslides, creating slope instabilities especially during extreme precipitation events. The spatial variability created by these operations leads to heterogeneous infiltration and runoff responses along hill slopes (Janeau et al. 2003; Ronchi et al. 2019).

4 Impact of Inorganic Fertilizers on the Soil Health

Sustainable agriculture is an important global issue (Zhu et al. 2021). Chemical fertilizers—like nitrogen, phosphorus, and potassium—are often applied to soil for improving its quality and its ability to provide the required nutrients for plant growth (Scherer 2000). Besides providing the nutrient for crop plants, fertilizer application has number of negative aspects on the soil, plants, and ecosystem as represented in (Fig. 6). This practice is considered as the most beneficial way and different chemical fertilizers usually enhance soil nutrient availability and increase nitrogen, phosphorus, and potassium available in soils (Adesemoye et al. 2009; Iqbal et al. 2021a, b). Indeed, exogenously applied chemical fertilizers have an impact on soil physical qualities. The application of nitrogen fertilizer is especially relevant for improving soil physical–chemical parameters (Lakhdar et al. 2009; Bhatt et al. 2019). Moreover, the application of chemical fertilizers increased cumulative infiltration and infiltration rate with time. Nitrogen fertilizer application improved SOC concentration that results in better soil physical properties, especially the infiltration rate (Bhattarai et al. 2012). A positive correlation exists between SOC and infiltration rate. The phosphate fertilizer, with organic matter application, improves the hydraulic conductivity and infiltration rate. The chemical fertilizer's effects on soil microbes are usually short term because soil pH changes only for a short time; the soil's buffer capacity helps attain the original soil pH (Iqbal et al. 2021a, b).

Short-term effects of anhydrous ammonia and urea application on soil were observed in a project in New South Wales. The total microbial activity was reduced by the application of ammonia and urea for 5 weeks and returned to normal thereafter. Large increase in nitrifying bacterial population occurs in the soil after 5 weeks of application while protozoa and their population reduced by about 80% and did not return to normal numbers after 5 weeks (Clarholm 1985; Velmourougane and Blaise 2017; Iqbal et al. 2021a, b).

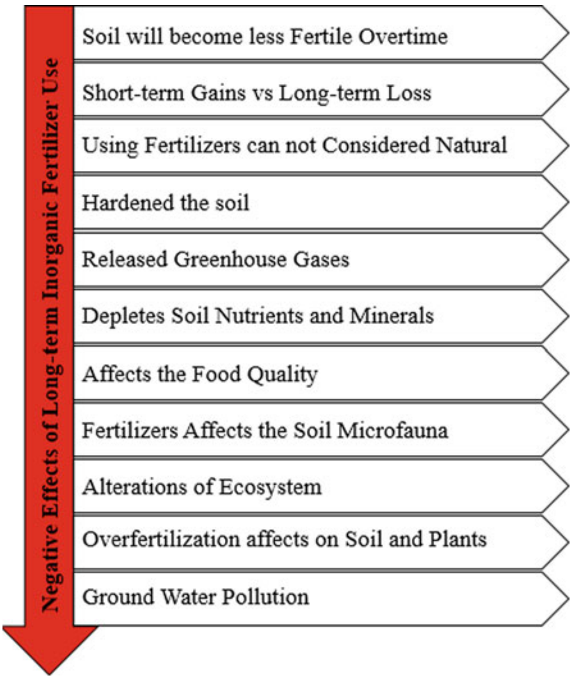


Fig. 6 Harmful effects of inorganic farming. *Source* Iqbal et al. (2021a, b)

5 Organic Amendments and Soil Health

The application of organic fertilizers is linked to soil organic carbon and nitrogen pools, which consequently change microbial parameters and plant nutrition (Buragohain et al. 2018). Number of organic amendments are commonly used for improving the crop productivity and soil health as depicted in (Fig. 7). The maintenance of soil organic matter is important for the long-term productivity of agro-ecosystems. Organic amendments applied to the soil are a management method to combat the increasing loss of organic matter (Marinari et al. 2000; Tejada et al. 2008a, b, c; Mangalassery et al. 2019).

The addition of organic amendments may improve soil physico-chemical, biochemical, and microbiological properties involved in biogeochemical cycles and thus positively influences plant productivity parameters. The organic amendments are a source of slow-releasing nutrients and available energy for soil microorganisms (Gómez et al. 2006; Mangalassery et al. 2019). Among the main benefits attributed to the use of organic amendments are improved soil aggregation, a decrease in bulk density, a greater water holding capacity, stabilization of pH, and increased CEC (Sasal et al. 2000; Tejada et al. 2008a, b, c). Less nutrient potential loss and particularly a reduction in the loss of nitrate are also quoted as positive effects of organic farming. As this could also promote plant health, it seems possible to obtain equivalent or even higher yields in organic production than with conventional farming (Bulluck et al. 2002; Mangalassery et al. 2019).

Fließbach et al. (2007) concluded that organic farming with composted manure is the only agricultural practice that can limit the decrease of soil organic carbon content. They showed that organic farming is the best agricultural practice for sustainable land management, in particular through the enhancement of soil microbial activity and

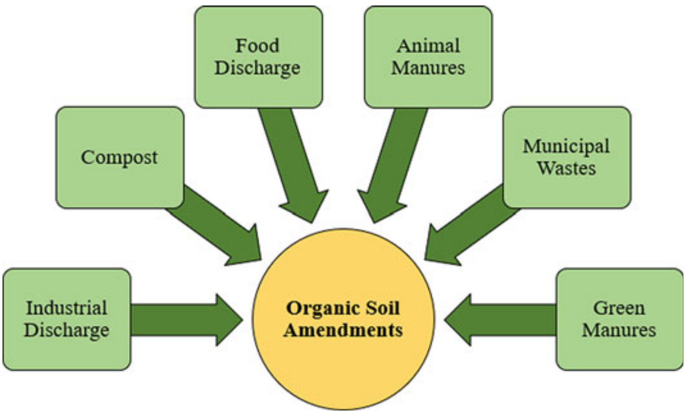


Fig. 7 Organic amendments: potential tools for soil and plant health. *Source* Nazir et al. (2021)

increased mineral exchange between plants and soil (Haynes and Mokolobate 2001). The use of amendments has been reported to increase the soil organic matter, provide nutrients, and improve the microbial activity (Lee et al. 2004; Mangalassery et al. 2019). The results are conditioned by the composition of amendments, the rate of application, and the soil type (Albiach et al. 2001; Tejada and Gonzalez 2003).

Furthermore, as soils are the basis of food production, preserving their quality with manure and low-chemical use is essential for sustainable land management, even if these farming systems are not the most productive. Less understood, however, are the effects of organic amendments on soil food webs, which contain the biotic assemblages responsible for the decomposition and generation of soluble nutrients for plant uptake (Tejada and Gonzalez 2003; Mangalassery et al. 2019). Maximizing the efficacy of organic amendments toward improving the soil health requires an understanding of how this practice affects the entire soil food web (beneficial and pathogenic/parasitic components) and how these effects are mitigated by other agricultural practices, such as tillage. However, tillage can also be used to incorporate amendments into the soil and therefore should expand their effect into deeper soil layers (Treonis et al. 2010; Azam and Gazey 2020).

The organic farming in Slovenia is part of an agro-environmental program. Slovenian farmers are supported by The Institute for Sustainable Development, are well organized in their own union, and have their own trademark ('Biodar'). The organic fruit production in Slovenia has steadily increased in recent years due to the excellent returns for growers. In 2011, almost 3% of Slovene farmers were registered as organic producers. Slovenia maintains natural conditions that allow for organic farming, often in combination with 'eco-tourism.' Whereas most people view organic food as being healthy, others are concerned about the food safety, which can be affected by potential pathogen sources in organic fertilizers or irrigation water. These views of food safety linked with organic production are interesting but require further studies to help people understand the healthy aspects of organic farming (Fließbach et al. 2007; Velmourougane and Blaise 2017).

6 Green Manuring and Soil Health

Green manuring (GM) is the practice of incorporation of undecomposed fresh/dry plant material into soils, either from the same place or brought from a distance (Pieters 1927). In addition to this, green manure legume crops also fix atmospheric N biologically. The biological nitrogen fixation (BNF) is a microbiological process in which atmospheric N_2 is converted into a plant-usable form, which offers an economically attractive and ecologically sound option of reducing external inputs and improving internal resources (Sulieman and Tran, 2014; Adekiya et al. 2019). Green manuring has become a very important agricultural practice in the last three decades, but the interest has gradually declined as fertilizers have become readily available. However, the reliance on synthetic fertilizers has proved to be detrimental for both human health and the environment. A dead zone has been created in the Gulf of Mexico due to the runoff of soils and such fertilizers (Pimentel et al. 2005; Yang et al. 2018).

Therefore, to provide for adequate production of quality food grains to feed an ever-growing population, green manuring practices are promising tools toward the sustainability of agriculture with limited impacts on the environment (Kumar et al. 2014a, b). Furthermore, the diminished crop productivity has resulted from the constant extraction of soil nutrients and poor soil management methods, such as excessive tillage and burning of vegetative wastes (Florentín et al. 2010). The soil management practices to increase fertility and productivity should include an increase in biomass along with reducing its decomposition (Bunch, 2012; Yang et al. 2018). Green manuring, on the other hand, being a practice in which the undecomposed plant material is turned back into the soil to provide organic material and nutrients can be considered as a suitable alternative that positively affects the physical, chemical, and biological properties of the soil (Fageria 2007). Giving proper attention and gaining knowledge regarding the composition, rates, and placement of GM crops, the application of fertilizers can be reduced drastically (Schröder 2005; Yang et al. 2018).

The potential benefits of green manures include pest management and weed control. However, the increased production cost of planting green manure led to minimize the farmers' acceptance of this approach, which is showing a lack of support for its sustainability (Ntakirutimana et al. 2019). Some of the commonly grown green manure crops are sun hemp, wild indigo, mung bean, urid, and soybean.

6.1 Effect of Green Manuring on Soil Health and Fertility Management

In the modern days of agricultural science, crop rotation and number of resource conservation technologies are commonly used to achieve sustainable production efficiently. Since continuous and conventional cultivation leads to a decline in soil OM content, reducing the soil's nutrients holding capacity results in a loss of soil sustainability. One of the major options to restore soil quality (especially in tropical soils) and reclaiming degraded soil is to increase soil OM content by GM (Kumar et al. 2010; Chimouriya et al. 2018). GM is eco-friendly, non-polluting, and non-hazardous to soil, water, and air (Yang et al. 2018). Moreover, like chemical fertilizers they do not exhibit any adverse effect on food commodities. GM with high nutrient concentrations and low C/N ratios has a great impact on their value as organic fertilizer in crop production (Talgre et al. 2012; Adekiya et al. 2019). The use of GM together with adequate residue management and crop rotation could be useful to conserve or increase soil fertility, promote nutrient cycling at the farm scale, smother weeds, and reduce the external nutrient inputs (Melero et al. 2006; Yadav et al. 2019). GM plants are mainly grown for the benefit of the soil and are very commonly referred to as soil fertility building crops.

In general, green manure enriches soil with organic matter and nutrients, improves soil physical, chemical, and biological properties, causes nutrient and soil conservation, increases the biochemical activity in soil, reduces soil compaction, increases soil porosity, water infiltration, and rooting depth, and finally enhances the crop health and yield (Golec et al. 2007; Bhattarai et al. 2012; Velmourougane and Blaise 2017). Although the main objectives of GM are to increase OM content and replenish soil nutrients, potential additional benefits from GM include reduced nitrate leaching and lowering the required N fertilizer application for succeeding crops (Fageria 2007). GM plants are raised between the main crops to reduce erosion, restore the productivity of exhausted land, protect fallow land from nitrate leaching, and replace chemical fertilizers (Xie et al. 2016; Yang et al. 2018).

6.2 Green Manuring in Relation to Physical, Chemical, and Biological Properties

The incorporation of GM plants increases soil organic matter levels, thereby improving soil physical conditions by enhancing soil aggregation, decreasing soil bulk density and soil compaction, and increasing the water- and nutrient-holding capacity, infiltration rate, and air and water movement in soil, besides that GM plants provides number of another beneficial role as represented in (Fig. 8) (Chimouriya et al. 2018). Interestingly, these soil physical characteristics encourage microbial proliferation so that mineralization and soil fertility are improved (Pandey and Singh 2016; Zaccheo et al. 2016; Nayak and Vaidya 2018; Adekiya et al. 2019). However, it is also true that the decomposition of the organics is different between leguminous and non-leguminous GM. Legumes decompose more quickly than non-legumes (Eriksen 2005) and consequently do little to long-term soil organic matter building. Yet legumes have a profound effect on microbial growth and their dynamics in the short term (Dubey et al. 2015).

However, in general, the effects of GM on soil physical properties may only become significant after growing several GM crops over a period of 5 to 10 years. The GM plant roots encourage aggregate stabilization and, consequently, influence the infiltration rate. The water holding capacity of sandy soils is increased when organic matter is added by decreasing pore sizes and reducing infiltration rates (Selvi and Kalpana 2009; Yadav et al. 2019). In addition, GM increases microbial growth and their dynamics in soil by releasing nutrients and root exudates, thereby improving the soil fertility and health. The soil microorganisms synthesize polysaccharide gums that bind soil particles, form soil aggregates, and build soil structure. Except for Brassicas and lupins, most of the green manures are known to maintain the soil mycorrhiza population, associated with the soil phosphorus nutrition. Additionally,

Fig. 8 Importance of green manuring. *Source* Chimouriya et al. (2018)

GM prevents water and wind erosion due to the root-soil binding effect (Schumann et al. 2000; Velmourougane and Blaise 2017) and protecting the soil surface by its coverage. It has been found that GM by lucerne, chicory, and red clover facilitates to break up compacted soil as they possess deep tap root system (Rayns and Rosenfeld 2010). GM between crop sequences prevents nutrients being lost from the soil.

GM serves as a source of nutrients and energy for countless number of soil organisms which are essentially helpful to maintain the soil health. The release of nitrogen, phosphorus, and potassium in soil from decomposing *Crotalaria juncea* L. was demonstrated earlier (Sinha et al. 2009; Adekiya et al. 2019); however, the rate of the nutrient release was found to be influenced significantly by climatic factors such as temperature and moisture as well as plant types (Saria et al. 2018). Buckwheat, lupin, oil radish, etc., are known to enrich soils with phosphorus. Lupin demonstrated more phosphorus uptake and its utilization than grain crops. Therefore, once GMs are incorporated in soil, phosphorus from their body will be released and will become available to the subsequent crop. GM has also been found to increase the phosphorus availability and utilization from rock phosphate in rice (Cavigelli and Thien 2003; Bah et al. 2004 2006; Velmourougane and Blaise, 2017). It has been shown that legume GM shifts the soil acidic pH to above 6.5 for 8–16 weeks, thereby enhancing the soil nitrogen, phosphorus, potassium, calcium, and magnesium status (Bah et al. 2004; Adekiya et al. 2019). However, the soil pH may be reduced due to organic acids and carbon dioxides released by GM roots and during their decomposition. Thus, GM affects soil pH significantly. GMs, more specifically the leguminous one, are primarily considered as a source of nitrogen, since they contain low C:N ratio.

Additionally, the leguminous type of GM, in association with specific type of microorganisms, can fix the atmospheric N and increase the soil N level after their incorporation in soil, while non-leguminous GMs increase the SOM content and do not fix atmospheric N (Tejada et al. 2008a, b, c). Therefore, the application of GM reduces the use of chemical N fertilizers and additionally improves the soil physical and biological properties by increasing SOC content (Pung et al. 2004). The soil microbes decompose organic substances present in soil and become instrumental to transform unavailable form of nutrients to their available form for crops. During the decomposition of plant residues in soil, the distribution and population dynamics of soil microorganisms are significantly influenced. Akpor et al. (2006), Bokhtiar et al. (2003), and Adekiya et al. (2019) reported that the GM with dhaincha and sunn hemp supplemented with urea at different levels exhibited an increase in sugarcane yield up to 57% along with the significant increase in SOM, total N, and the available P and S in the soil. The N loss from soil amended with GM is considered significantly low compared to chemical nitrogenous fertilizers. Thus, the GM application to soil minimizes air (acid rain, global warming, etc.) and water pollution (eutrophication, nitrate toxicity, etc.). About 14–35% loss of nitrogen was demonstrated in flooded soil with applied GM and split dose of urea, respectively. This might be due to the synchronization of demand and supply of nitrogen as GM acts as a slow-release nitrogen source.

The importance of GMs in the improvement of soil CEC has been demonstrated by many researchers (Kimetu et al. 2008; Saria et al. 2018). Therefore, it may be concluded that GMs protect the cation from leaching out of the plant root zone and makes them available to plant roots. The use of GM has the potential to improve crop growth accompanied with both quantitative and qualitative yield as compared to N, P, and K fertilizers. It is proved that the nutritional effects of GMs on soil and crop plants depend on their residue quality (Agbede 2018; Adekiya et al. 2019). Therefore, the choice and selection of GMs also play a pivotal role for the beneficial discharge to the succeeding crop, considering both qualitative and quantitative aspect of the crop yield. Out of four GMs—Moringa (*Moringa oleifera* Lam.), Pawpaw (*Carica papaya* L.), Neem (*Azadirachta indica* A. Juss.), and Mesquite (*Prosopis Africana* Guill., Perr. and A. Rich)—Moringa leaves were found to be the best green manure improving the fruit quality of Okra in terms of K, Ca, Fe, Zn, Cu, and vitamin C contents compared with other green manures (Adekiya et al. 2019). They recommended Moringa for obtaining the quality of okra fruits and Mesquite for the quantity. Likewise, cassava productivity was increased by Gliricidia, while Moringa improved root quality (Agbede 2018). Overall, GMs—such as Neem (*Azadirachta indica* A. Juss.), Moringa (*Moringa oleifera* Lam.), Gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.), and Leucaena (*Leucaena leucocephala* (Lam.) de Wit)—were found to increase mineral and starch contents and reduced HCN content in the cassava tuber roots compared with the control (Agbede 2018). Such variations might be due to the varied potential of GM plant materials to improve the soil quality because of the difference in their chemical composition, rate of degradation, extent of released nutrient elements in soil, and, in turn, their influence on the crop uptake (Tóth et al. 2007).

It has been observed that the microbial populations, their growth, and diversity are significantly influenced with GM and soil admixture. This might be attributed to the fact that easily available energy and nutrient source through GM was delivered to the soil microbial community, which stimulate their activity and growth. More microbial proliferation leads to more extra cellular enzymes, and their favorable abundance causes major transformations of nutrients from plant unavailable forms to their available forms. During 4 years of continuous experiment with ryegrass (*Lolium* *multiflorum* L.) application to soil, the soil microbial biomass carbon (Cmic) and nitrogen (Nmic), soil respiration, soil enzymatic activities such as urease, invertase, and catalase were increased as compared to the control treatment (Ye et al. 2014). GM, *Trifolium pratense* L. applied @ 25 t/ha increased Cmic by 79.2% (Tejada et al. 2008a, b, c). The increase in microbial Cmic and Nmic, their size, and activity were also observed by several other researchers (Elfstrand et al. 2007; Ochiai et al. 2008; Velmourougane and Blaise 2017).

To increase the agricultural production in conventional agriculture, chemical N fertilizers are often overused to such an extent that the environment is adversely affected. The concentrations of several reactive oxidized and reduced forms of N—such as NO_x, N_2O, NO_3, and NH_3—are reported to exhibit an increase in their concentrations in the environment (Fagodiya et al. 2017; Meena et al. 2018). Obviously, this alarming hike in N species in the environment is not only due to chemical fertilizers, but also due to other agricultural practices, such as crop stubble burning after harvesting, and emissions from various industrial units. Nevertheless, the biological N fixation (BNF) from the atmosphere should be a better option to reduce using chemical fertilizers that cause water pollution (NO_3), air pollution (NO_x), and climate change (N_2O) (Sulieman and Tran 2016).

Under practical situations in organic systems, the leguminous GM acts as the main source of N. Nowadays, in conventional system, also, legume GMs are used extensively primarily to minimize chemical fertilizer application and to build up organic C pool in soil. Improved organic matter level in soil helps increase the soil N as there exists a positive correlation between them. The soil N level can be improved with improving levels of SOM. The application of legume GM is an important option to optimize the BNF and to ensure soil sustainability (Meena et al. 2018). Legumes in mutualistic symbiotic association with soil bacteria, called N-fixers, (Rhizobia) can fix the nitrogen from atmosphere and enrich the soil with nitrogen through mineralization, once they are decomposed after their incorporation in soil (Adekiya et al. 2019). In this process of BNF, the plants act as the C and energy source for the bacteria which reside in the roots, forming nodules and in turn, supply N to the plant. The available N present in the soil is critical to determine the extent of N fixation. If there is an abundance of the available N in soil during plantation of legume, GM prefers to use available form of N from soil instead of fixing them from the atmosphere. Therefore, to maximize the soil fertility gain through leguminous GM, one should be careful during its placement in crop sequence and current soil fertility status (Meena et al. 2018).

7 Crop Residues Management and Soil Health

The residue from cereal crops (wheat and rice) is managed and used in several ways (Mendoza and Mendoza 2016). Burning, composting, residues removing, residues incorporation, bailing, and surface retention are the most notable techniques that are most commonly used in sustainable agriculture (Chen et al. 2019) (Fig. 9). In Indian

Subcontinent, the crop residues burning is common practice that have number of negative effects as depicted in (Fig. 10). Those farmers that raise livestock remove the residue to feed their animals or allow their own or neighbors' livestock to graze on their fields. Some sell it to be used as animal fodder or as biofuel to supplement their income, while others still burn it because there is no market for the crop residue or remove it because it is sometimes easier to use machinery without crop residues on the field (Turmel et al. 2015; Kumar et al. 2018). In the case that crop residues are retained, they may either be left on the soil surface or incorporated into the soil (Blanco-Canqui and Lal 2009). These different residue retention practices are associated with different tillage practices, and thus, it can be difficult to separate the effects on the soil quality. Conventional tillage (CT) practices often involve initial tillage by moldboard plowing, followed by secondary tillage by disking, harrowing, or field cultivating (Maneepitak et al. 2019).

This form of tillage buries all superficial crop residues in the soil. Farmers in developing countries with poor access to herbicides rely on tillage for weed control, thus incorporating residues in the process. Some farmers, in regions where open range grazing is practiced such as the Central Mexican Plateau, opt to incorporate their residues to protect them from grazing by their neighbor's animals. 'Winter plowing,' i.e., plowing crop residues into the soil after harvest when the soil is still moist, is also a common practice in certain areas of Southern Africa (Reicosky et al. 1995; Bista et al. 2017).

Retaining the crop residue on the soil surface is considered by many to maintain physical, chemical, and biological properties in agricultural soils. Agricultural systems using zero or reduced tillage, such as conservation agriculture, recommend a permanent or semi-permanent organic soil cover (Farooq and Siddique 2015).

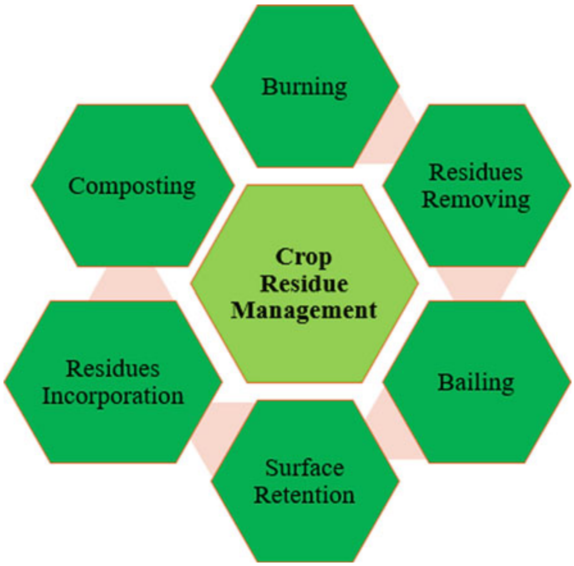


Fig. 9 Management options for crop residues. *Source* Nazir et al. (2021)

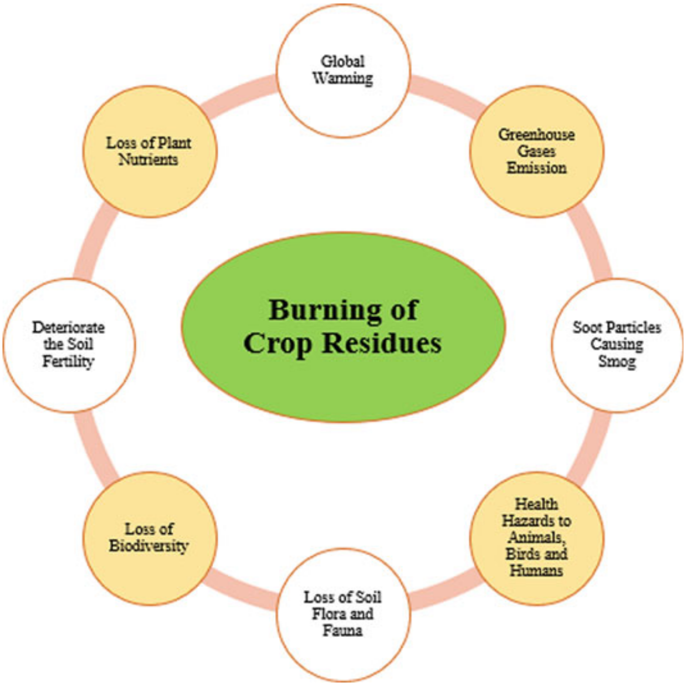


Fig. 10 Negative effects of crop residues burning. *Source* Nazir et al. (2021)

Some general types of conservation tillage that retain crop residue, leaves, and roots on or near the surface include chiseling, stubble mulching, and no-till (NT) (Mondal et al. 2020). When using NT systems, it is particularly essential to leave residue on the surface rather than remove it as the combination of NT with residue removal or burning may have an even greater negative effect on the soil quality in the long-term than CT practices due to excessive soil compaction and reduced water infiltration (Gómez et al. 2006; Velmourougane and Blaise 2017).

7.1 Influence of Crop Residue and Biochar on Soil Quality

The crop residue returns organic matter to the soil where it is retained through a combination of physical, chemical, and biological activities that interact and affect the soil quality, including nutrient cycling (Coonan et al. 2020). The influence of residue management on some important chemical properties (soil organic carbon, soil pH, and cation exchange capacity), on physical properties (soil structure, runoff, erosion, soil compaction, soil temperature, and moisture content), and on biological properties (soil biodiversity and soil microbial biomass) are discussed below in (Fig. 11). Crop yield results that may be presented in this chapter are done so in the context of the

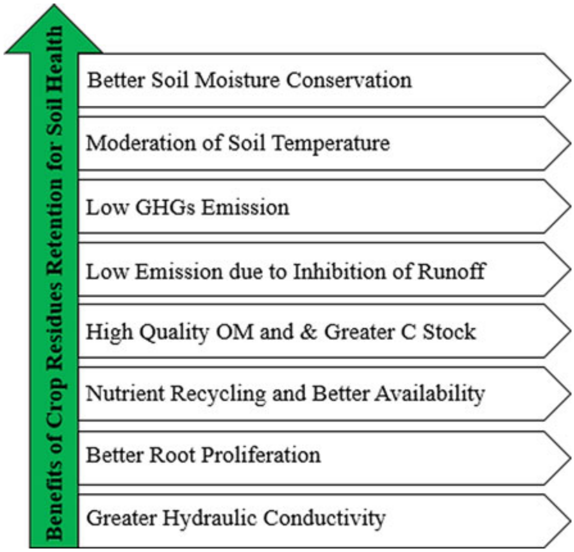


Fig. 11 Importance of crop residues retention for improving soil fertility. *Source* Nazir et al. (2021)

contribution to crop residue after harvest, since greater crop yields will leave greater crop residue after harvest (Chao et al. 2019). Moreover, if better yields allow for sufficient levels of crop residue cover, then a greater quantity of residue will be available for animal feed, development of paper, and in compost formation (Gómez et al. 2006; Yadav et al. 2021).

Many recent studies concluded that biochar might be able to modify the soil bulk density and soil moisture content. For instance, biochar produced from date palm reduced the bulk density and increased field capacity (FC) of sandy soil compared with un-amended soil (Khalifa and Yousef 2015; Al-Omran et al. 2019). Mangrich et al. (2015) produced biochar from oil palm and conducted a study to investigate the water holding capacity of sandy soil. They found that this water holding capacity was increased by adding oil palm biochar. Laghari et al. (2015) studied the effect of the application of pine sawdust biochar (22 t ha^{-1}) on hydraulic properties of sandy soil. They reported that, compared with untreated sandy soil, the hydraulic conductivity decreased by 32–7%, water retention capacity increased by 28–32%, and the water holding capacity increased by 11–14% depending on the sand type.

In a most specific study, Ibrahim et al. (2017) analyzed the sandy soil columns under laboratory conditions to identify the impacts of soil-biochar layer and the applying depth (D0, D5 and D10) on the behavior of hydro-physical properties. They found that the soil water conserved were 14.32, 15.14, and 13.26% for S1 (biochar particle size < 0.5 mm), 12.48, 18.03, and 11.72% for S2 (0.5–1), and 11.58, 13.41, and 6.32 for S3 (1–2) mm. Similar findings reported by Ibrahim et al. (2013) show that cumulative evaporation was decreased by 5.4–12.1% because of increasing rate of biochar addition. Thus, the field capacity (FC) increased by 7.2–15.9% at surface layer. Also, they proved that adding biochar at rates of 5, 10, 15, and 20 g kg^{-1} to soil makes significant effects on the retainment of soil water by 8.9%, 17.6%, 28.1%, and 30.9%, respectively.

7.2 Influence on Soil Chemical Properties

Soil Organic Carbon

Soil organic carbon (SOC) is considered an important indicator of soil quality and agricultural sustainability because it improves soil aggregate stability and soil water retention, and provides a reservoir of soil nutrients (Kumar et al. 2014a, b; Bongiorno et al. 2019). SOC is naturally removed from the soil through soil heterotrophic and autotrophic respiration, where carbon (C) is released as CO_2. However, human activities such as land-use changes, in particular the conversion to agricultural fields and pasture, removal of crop residues and direct feeding to livestock, release even greater amounts of C into the atmosphere as CO_2. The agricultural practices disturb the SOC pool, which represents a large potential source of greenhouse gasses; soil C loss can thus lead to lower soil quality and pressure on sustainable crop production and food security (Jarecki and Lal 2003; Jayaraman et al. 2021a, b).

Crop residue retention and biochar application are key steps to increasing and/or maintaining SOC levels; however, its effect may be controlled by soil type and climate and management factors. For example, in Zimbabwe, Rusinamhodzi et al. (2015) measured higher SOC in sandy soils under the mulch ripping treatment with residue retention compared to clean ripping with residue removed and attributed this to the residue retention. The soil type (sandy soil with greater coarse fractions) appeared to play a role since no significant differences in SOC were observed in red clay soils with the same experiment.

Management factors, such as incorporating by tillage or leaving crop residue on the soil surface, can additionally influence the effect of crop residue retention on SOC in the soil profile. Conventional tillage is usually considered responsible for C losses by increasing decomposition rates (Reicosky et al. 1995; Jayaraman et al. 2021a, b). The tillage disturbs soil structural stability and redistributes organic matter, thus influencing the microbial activity at the soil surface that releases carbon. In this way, the cultivation has led to a 30–50% reduction in pre-cultivation SOC levels in agricultural soil. However, a meta-analysis of soil C case studies found inconclusive results. In 7 of the 78 cases examined, the soil C stock was lower in zero-tillage compared to conventional tillage; in 40 cases, it was higher, and in 31 cases, there was no significant difference. In choosing adequate management practices, understanding decomposition and SOM stabilization is key in predicting the fate of carbon, as well as nutrients, added to the soil through crop residue and other soil amendments (Dignac et al. 2017).

Soil pH

The retention of crop residues can affect the soil pH since the direction of change in soil pH is related to the chemical composition of the residue and soil properties (Chen et al. 2013). Residues high in ash alkalinity and nitrogen such as some legume residues will have a greater effect on pH compared to residues with lower content such as wheat. Moreover, soil properties that affect the rate of residue decomposition, such as texture, moisture content, temperature, available N, SOC, and initial pH, control the effect of the residue on soil pH. Changes in pH from crop residue addition are correlated with the concentration of organic anions in the residue and the nitrogen content of the residue (Xu et al. 2006; Vanzolini et al. 2017). The effect of residue retention on pH is generally restricted to the topsoil layer; however, it remains unclear whether incorporation versus surface retention has an influence. In central Mexico, it was observed that after five years, pH was higher (7.0) in the 0–5 cm surface layer when maize and wheat residues were retained on the surface compared to remove (6.6) or incorporated with conventional tillage (6.7), but there was no significant effect in the subsoil layer (5–20 cm).

Cation Exchange Capacity

Cation exchange capacity (CEC), as an indicator of the soil fertility, is the capacity of the soil to hold cations for exchange with the soil solution. The soil residue retention increases SOM content and thus increases the soil's pH-dependent CEC. As with SOM, the effect of residue on CEC may be limited to the topsoil layer (Turmel et al. 2015; Purnamasari et al. 2021), and it remains unclear whether there is a difference between surface retention vs. incorporation. It was observed that after 5 years, CEC increased in the topsoil when residues where retained compared to soils without residue, but there was no difference in the 5–20 cm layer. In West Africa, it was observed that while residue retention increased CEC both when residues were retained on the surface and incorporated, the increase in CEC was greatest when residues were retained on the surface (Naresh et al. 2017).

Nutrient Availability

The addition of crop residues can influence the availability of nitrogen to the crop. The addition of legume residues with a low C/N composition can result in N mineralization, whereas cereal residues with a high C/N composition can temporarily immobilize N during the decomposition process. Denitrification losses of mineral nitrogen fertilizer can also be greater when residues are left on the surface due to higher soil moisture content and if fertilizers are not properly incorporated. The residue retention has been found to increase the concentration of P in the top soil. This can be attributed to the redistribution of P mined from the lower soil layers (Hedley et al. 1982; Choa et al. 2019). Also, in strongly weathered soils, the addition of residues can indirectly increase the availability of phosphorus. Humic molecules and low molecular weight aliphatic acids released during the decomposition of crop residues can block Al-oxide adsorption sites and reduce overall adsorption of P (Deng and Dixon 2002; Webster et al. 2021). This effect is dependent on the quality of the residue; legumes are generally more effective due to increased decomposition rates.

7.3 Influence on the Soil Physical Properties

Soil Structure

The surface residue retention plays an important role in protecting soil aggregates from the raindrop impact. The residue cover is the most important factor in dissipating the impact of rainfall, thus preventing soil aggregates from breaking down (Jayaraman et al. 2021a, b). In the Yaqui Valley in the state of Sonora, Mexico, the surface residue is used for animal feed or tilled into the soil, and the irrigation water is becoming increasingly scarce like in other regions worldwide (Anum et al. 2021). Comparing conventional tillage and zero-tillage under full and reduced irrigation both with residue retention, Roberts et al. (2005) noted an increased aggregate stability in the 0-5 cm layer in permanent raised beds compared to conventionally tilled beds due to the surface residue protection from raindrop impact. Further, leaving residues on the surface protects the soil from surface compaction. Porosity, water content, water infiltration, and air movement are all reduced when soil is compacted. Soil bulk density increases under compaction, which can affect nutrient availability, and hence crop growth, and lead to nutrient input losses through surface runoff. The effects of crop residue on soil compaction depend on the residue management practice, the machinery use, the duration of the study, and the soil texture. Without residue, the soil compaction can increase significantly after continuous NT over a number of years. In addition, compaction causes seal-over and crusting that lead to runoff and erosion, thus reducing the soil quality. In northwestern Mexico, the penetration resistance was highest in soils with zero-tillage and burnt crop residue (Roberts et al. 2005; Velmourougane and Blaise 2017). With residues on the surface, the higher infiltration rates under NT were recorded compared to NT without residue retention, indicating that the negative effects of soil compaction can be avoided by retaining the surface residue.

Surface Runoff and Soil Loss

The residue retention on the soil surface can also provide physical soil protection against water and soil loss. In addition, crop residues cause a lower sediment load in surface runoff during the rainfall (Liu et al. 2019). In a crop management experiment with simulated rainfall applications in southwestern Brazil, it was observed high runoff and soil loss under NT without residue, significantly less under NT with 2 t ha1 of surface soybean residue, and no runoff or soil loss under NT with 4 t ha1 of surface soybean residue. The water infiltration rates were likewise higher in NT with surface residue. The high water and soil losses from NT without surface residue were likely due to the hardening of the soil surface caused by rain impact in the absence of ground cover, which increases the surface runoff and decreases the water infiltration (Roberts et al. 2005; Liu et al. 2019). The protective influence of residue retention on the surface was further emphasized by the high runoff and soil loss levels in the disk-harrow treatments with 2 and 4 t ha1 of soybean residue, which were incorporated rather than left on the soil surface (Jayaraman et al. 2021a, b).

Soil Moisture Contents

Moisture retention is considered one of the main benefits of surface residue cover, in terms of yield increase in rainfed climates where crop production is limited by soil moisture. In another part of the Himalayas, in the northeastern region of India, water is scarce as rainwater runs off slopes. On the ground level, rice is produced and the crop residue is removed for animal feed or burned after harvest; traditional plowing practices add to soil degradation. A rice system study within the region comparing NT with surface residue, minimum tillage with residue incorporation, and CT with residue removed revealed that both NT and minimum tillage treatments with residue maintained higher soil moisture (Bandyopadhyay et al. 2010; Jayaraman et al. 2021a, b).

In the valley upland area under a rice-pea rotation with NT, Bandyopadhyay et al. (2010) reported better pea crop performance with 75% and 50% rice residue on the soil surface. This was ascribed to increased water retention by the residue cover since NT without surface residue exhibited water loss. Roberts et al. (2005) found similar results in the semi-arid, subtropical highlands of central Mexico. After 15 years, NT with residue had higher soil moisture content than CT with or without residue or NT with residue removed. The average maize yields during this time were higher in NT with residue compared to CT and NT without residue, reflecting more crop resilience during dry periods. For example, in semi-arid areas with small and frequent rainfall events, residue cover can intercept rainfall and increase subsequent evaporation. Conversely, in areas with excess rainfall, the residue retention can lead to excessive soil moisture and water logging (Turmel et al. 2015; Liu et al. 2019).

Soil Temperature

Retaining residues on the soil surface has been noted to decrease daytime soil temperature (Roberts et al. 2005; Devi et al. 2019). In hot, tropical climates, this effect is beneficial since soil temperature may be too high for optimum plant growth, whereas in cooler climates the effect can be detrimental to plant development. It was noticed that mulching has positive effect on the soil temperature and noticeable change was observed under minimum tillage with mulch treatments compared to the CT with no-mulch treatment. This created a more favorable environment for root growth. The lowering effect of surface residue on temperature is consistent with results of other studies as well (Turmel et al. 2015).

Alternatively, the residue can be removed from the seed zone only, in order to still maintain the beneficial effects of the residue retention. In southern Ontario, Canada, it was observed that NT with a 30 cm band of bare soil along the corn row had a higher seed zone temperature than regular NT with full residue cover, but still had the NT advantage of lower evaporation compared to CT. Despite differences in seed environment, no differences in seed emergence after 20 days or in grain yield between the treatments were reported. More studies are required to examine whether NT in-row residue removal (or strip tillage) leads to higher grain yields compared to regular NT with residue retention (Turmel et al. 2015; Darapuneni et al. 2019).

7.4 Influence on the Soil Biological Properties

The soil biodiversity consists of soil microflora (e.g., bacteria, fungi) and soil fauna, which is classified by size as microfauna (e.g., nematodes, protozoa), mesofauna (e.g., acarids, enchytraea), and macrofauna (e.g., earthworms, termites, large arthropods). These organisms can also be described through the soil food webs, with microflora and microfauna breaking down organic matter, mesofauna feeding on them, and macrofauna in turn feeding on mesofauna (Kladivko 2001). The soil biodiversity plays a large role in agro-ecosystems by affecting the crop quality, the occurrence of soil-borne pests and diseases, the nutrient cycling, and the water transfer. It can also reflect disturbance and stress, as the low soil biodiversity is often due to a human-caused disturbance (Rapport et al. 1985; Devi et al. 2019).

Microbial Activity

The residue retention is an important factor in stimulating SMB and the microbial activity. Turmel et al. (2015), in comparing treatments with straw retained and straw removed in Northeast China, found significantly higher microbial biomass C levels when straw was retained because of improved C and N contents, increased soil moisture and porosity, and decreased soil temperature caused by the residue cover. Similarly, in studies carried out in central Mexico, higher SMB with residue retained compared to without residue were recorded (Turmel et al. 2015). The incorporation of crop residues in the soil increases soil temperature and aeration, thus creating favorable conditions for microorganisms and greater contact between them and the residues, which lead to higher decomposition rates and the overall SOC loss (Parr and Papendick 1978; Li et al. 2018). This is consistent with the observation that fluctuations in the total organic C pool due to changes in C supply from crop residues are reflected in the microbial biomass. In tropical and subtropical areas with high temperatures and rainfall, no-till and surface crop residue have been observed to increase SOC content in surface soils compared to incorporation (Florentín et al. 2010; Rigon et al. 2021). This is due to less contact between surface residue and microorganisms in no-till systems, as described earlier, suggesting the importance of retaining residue on the surface rather than incorporating residues in sub-humid temperate to sub-humid tropical regions where decomposition rates are high (Turmel et al. 2015).

Earthworms

Earthworms have been observed to respond positively to the crop residue retention and the minimum soil disturbance. The cooler soil temperature, improved soil structure, and food resource provided by crop residue retained on the surface can lead to increases in earthworm number and biomass (Chan 2001; Balota and Chaves 2011). In contrast, the process of incorporating residue into the soil through tillage has been shown to have a negative impact on some earthworm species because tillage causes physical harm, exposes them to predators on the surface, and destroys their burrows (Chan 2001; Melman et al. 2019). In a semi-arid zone of Tunisia, for example, Chan (2001) observed that no-tillage with surface residue increased the soil invertebrate, including anecic earthworm, and population numbers and diversity compared to conventional tillage because of improved soil properties and lack of soil disturbance.

8 Conclusion

This chapter highlights the need for understanding the effects of bioresource management practices on the soil health. The effects of the bioresource management vary with soil types, climatic conditions, field management, and cropping systems. The strategies for improvement in soil health indices require the understanding of number of interactions among soil biological community, diversity, and management practices. The organic matter, through bioresources at the soil surface, root and cover crops, animal manure, green manure, compost, and biochar, improves the quality attributes of the soil. The incorporation of crop residues was found to be a technically sound practice over its removal or burning, because it recycled a substantial amount of nutrients to the soil along with organic matter.

Due to the porosity and ability to create air pores within the soil, biochar has a potential in reducing soil compaction. With this development, biochar can be used as a sustainable tool for the agricultural soil development. For boosting the bioeconomy of farmers, the transformation of agricultural biowaste into a useful bioproduct ensures the agricultural sustainability in terms of a closed-loop sustainability framework. With attributes of success of improving the bioeconomy at small and large scales, farmers can recycle their crop residues and benefit from a circular resource economy. The efficient management of bioresources improves the soil health indices at a low cost instead of spending on the purchase of commercially produced products that have the same nutrient status. The bioresource management is therefore a sustainable partway to the circular bioeconomy. Overall, it is inferred that bioresource management practices could be a better option for nutrient recycling, to sustain the crop productivity and soil health in the intensive agriculture system in Pakistan as well as in collateral global agroecological situations, especially China, India, and Bangladesh.

References

Adekiya AO, Agbede TM, Aboyeji CM, Dunsin O, Ugbe JO (2019) Green manures and NPK fertilizer effects on soil properties, growth, yield, mineral and vitamin C composition of okra (*Abelmoschus esculentus* (L.) Moench). J Saudi Soc Agric Sci 18:218–223

Adesemoye AO, Torbert HA, Kloepper JW (2009) Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microb Ecol 58(4):921–929

Agbede TM (2018) Effect of green manure application on cassava (*Manihot esculenta* Crantz) growth, yield quantity and quality in degraded alfisols. Pertanika Journal of Tropical Agriculture Science 41(4):1757–1777

Akpor OB, Okoh AI, Babalola GO (2006) Culturable microbial population dynamics during decomposition of *Theobroma cacao* leaf litters in a tropical soil setting. J Biol Sci 6(4):768–774

Alkhasha A, Al-Omran A (2020) Evaluating the effects of biochar and SAP polymer on soil physical quality indices. Commun Soil Sci Plant Anal 51(8):1123–1135

Al-Omran A, Ibrahim A, Alharbi A (2021) Effects of biochar and compost on soil physical quality indices. Commun Soil Sci Plant Anal 1–18

Al-Omran A, Ibrahim A, Alharbi A (2019) Evaluating the impact of combined application of biochar and compost on hydro-physical properties of loamy sand soil. Commun Soil Sci Plant Anal 50(19):2442–2456

Albiach R, Canet R, Pomares F, Ingelmo F (2001) Organic matter components and aggregate stability after the application of different amendment to a horticultural soil. Biores Technol 76:125–129

Amelung W, Bossio D, de Vries W, Kögel-Knabner I, Lehmann J, Amundson R, Chabbi A (2020) Towards a global-scale soil climate mitigation strategy. Nat Commun 11(1):1–10

Andrews SS, Caroll CR (2002) Designing a soil quality assessment for sustainable agro ecosystem management. Ecol Appl 11(6):1573–1585

Anum W, Ali L, Zulqadar SA (2021) Irrigation water status in pakistan, challenges and management strategies: a mini review. J Qual Assur Agric Sci 1(1):14–21

Azam G, Gazey C (2020) Slow movement of alkali from surface-applied lime warrants the introduction of strategic tillage for rapid amelioration of subsurface acidity in south-western Australia. Soil Research 59(1):97–106

Bah AR, Zaharah AR, Hussin A (2004) Effect of interactions on the nutrient status of a tropical soil treated with green manures and inorganic phosphate fertilizers. Sci World J 4:393–414

Bah AR, Zaharah AR, Hussin A (2006) Phosphorus uptake from green manures and phosphate fertilizers applied in an acid tropical soil. Commun Soil Sci Plant Anal 37:2077–2093

Balota EL, Chaves JCD (2011) Microbial activity in soil cultivated with different summer legumes in coffee crop. Braz Arch Biol Technol 54(1):35–44

Bandyopadhyay KK, Misra AK, Ghosh PK, Hati KM (2010) Effect of integrated use of farmyard manure and chemical fertilizers on soil physical properties and productivity of soybean. Soil and Tillage Research 110(1):115–125

Bhaduri D, Purakayastha TJ, Pramanik P, Saha A, Verma BC, Shahid M, Saha D (2020) Indexing Methods of soil quality in agro-ecosystems: an overview of Indian soils and beyond. Soil Anal Recent Trends Appl 255–284

Bhatt M, Singh AP, Singh V, Kala DC, Kumar V (2019) Long-term effect of organic and inorganic fertilizers on soil physico-chemical properties of a silty clay loam soil under rice-wheat cropping system in Tarai region of Uttarakhand. J Pharmacog Phytochem 8(1):2113–2118

Bhattarai N, Vaidya GS, Baral B (2012) Effect of mycorrhizal soil and green manures on growth of Ipil (*Leucaena diversifolia* L.). Sci World 10(10):66–69

Bista, P., Machado, S., Ghimire, R., Yorgey, G. and Wysocki, D. (2017). Conservation tillage systems. *Advances in Dryland Farming in the Inland Pacific Northwest'.(Eds G Yorgey, C Kruger) pp*, 99–124.

Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. Crit Rev Plant Sci 28:139–163

Bokhtiar SM, Gafur MA, Rahman ABMM (2003) Effects of *Crotalaria* and *Sesbania aculeata* green manures and N fertilizer on soil fertility and the productivity of sugarcane. J Agric Sci 140:305–309

Bongiorno G, Bünemann EK, Oguejiofor CU, Meier J, Gort G, Comans R, de Goede R (2019) Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecol Ind 99:38–50

Borselli L, Torri D, Øygarden L, De Alba S, Martínez-Casasnovas JA, Bazzoffi P, Jakab G (2006) Land levelling. In: Boardman J, Poesen J (eds) Soil erosion in Europe. Wiley, New York

Bulluck LR, Brosius M, Evanylo GK, Ristaino JB (2002) Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. Appl Soil Ecol 19:147–160

Bunch, R. (2012). Restoring the soil. A guide for using green manure/cover crops to improve the food security of smallholder farmers. Canadian Food grains Bank, Winnipeg, Canada.

Buragohain S, Sarma B, Nath DJ, Gogoi N, Meena RS, Lal R (2018) Effect of 10 years of biofertiliser use on soil quality and rice yield on an Inceptisol in Assam, India. Soil Res 56(1):49–58

Cavigelli MA, Thien SJ (2003) Phosphorus bioavailability following incorporation of green manure crops. Soil Sci Soc Am J 67(4):1186–1194

Ceja-Navarro JA, Rivera-Orduna FN, Patiño-Zúñiga L, Vila-Sanjurjo A, Crossa J, Govaerts B, Dendooven L (2010) Phylogenetic and multivariate analyses to determine the effects of different tillage and residue management practices on soil bacterial communities. Appl Environ Microbiol 76(11):3685–3691

Chan KY (2001) An overview of some tillage impacts on earthworm population abundance and diversity—implications for functioning in soils. Soil Tillage Res 57(4):179–191

Chan KY, Heenan DP, So HB (2003) Sequestration of carbon and changes in soil quality under conservation tillage on light-textured soils in Australia: a review. Austr J Experim Agric 43:325–334

Chen H, Li X, Hu F, Shi W (2013) Soil nitrous oxide emissions following crop residue addition: a meta-analysis. Glob Change Biol 19(10):2956–2964

Chen J, Gong Y, Wang S, Guan B, Balkovic J, Kraxner F (2019) To burn or retain crop residues on croplands? An integrated analysis of crop residue management in China. Sci Total Environ 662:141–150

Chimouriya S, Lamichhane J, Gauchan DP (2018) Green manure for restoring and improving the soil nutrients quality. Int J Res 5(20):1064–1074

Chao P, Kan ZR, Liu P, Qi JY, Zhao X, Zhang HL (2019) Residue management induced changes in soil organic carbon and total nitrogen under different tillage practices in the North China Plain. J Integr Agric 18(6):1337–1347

Clarholm M (1985) Interactions of bacteria, protozoa and plants leading to mineralization of soil nitrogen. Soil Biol Biochem 17(2):181–187

Coonan EC, Kirkby CA, Kirkegaard JA, Amidy MR, Strong CL, Richardson AE (2020) Microorganisms and nutrient stoichiometry as mediators of soil organic matter dynamics. Nutr Cycl Agroecosyst 117:273–298

Darapuneni MK, Idowu OJ, Lauriault LM, Dodla SK, Pavuluri K, Ale S, Angadi SV (2019) Tillage and nitrogen rate effects on corn production and residual soil characteristics. Agron J 111(3):1524–1532

De Deyn GB, Kooistra L (2021) The role of soils in habitat creation, maintenance and restoration. Philos Trans R Soc B 376(1834):20200170

Dejene M, Lemlem M (2012) Integrated agronomic crop managements to improve tef productivity under terminal drought. In: Rahman IMM, Hasegawa H (eds) Water stress. InTech Open Sci 235–254

Deng Y, Dixon JB (2002) Soil organic matter and organic-mineral interactions. Soil Mineral. Environ. Appl. 7:69–107

Devi NU, Pavan S, Rao KS (2019) Chapter-5 Soil Faunal diversity and their functional roles in enhancing the soil fertility. Curr. Res. Soil Fertility 19:77

Dignac MF, Derrien D, Barre P, Barot S, Cécillon L, Chenu C, Basile-Doelsch I (2017) Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agron Sustain Dev 37(2):14

Dokoohaki H, Miguez FE, Laird D, Horton R, Basso AS (2017) Assessing the biochar effects on selected physical properties of a sandy soil: an analytical approach. Commun Soil Sci Plant Anal 48(12):1387–1398

Doran JW (2002) Soil health and global sustainability: translating science into practice. Agr Ecosyst Environ 88:119–127

Dubey L, Dubey M, Jain P (2015) Role of green manuring in organic farming. Plant Architect 15(1):23–26

Efthimiadou A, Bilalis D, Karkanis A, Froud Williams B (2010) Combined organic/inorganic fertilization enhances soil quality and increased yield, photosynthesis and sustainability of sweet maize crop. Aust J Crop Sci 4(9):722–729

Elfstrand S, Hedlund K, Mårtensson A (2007) Soil enzyme activities, microbial community composition and function after 47 years of continuous green manuring. Appl Soil Ecol 35(3):610–621

Enya, O. O. (2019). Soil carbon dynamics in the upper Mersey estuarine floodplain, northwest England: implications for soil carbon sequestration (Doctoral dissertation, University of Salford).

Eriksen J (2005) Gross sulphur mineralization-immobilization turnover in soil amended with plant residues. Soil Biol Biochem 37:2216–2224

Erkossa T, Itanna F, Stahr K (2007) Indexing soil quality: a new paradigm in soil science research. Aust J Soil Res 45:129–137

European Commission. (2002). Towards a thematic strategy for soil protection. Communication from the commission to the council, the European Parliament, the Economic and Social Committee and the Committee of the Regions, European Commission, Brussels, 35p

Fageria NK (2007) Green manuring in crop production. J Plant Nutr 30(5):691–719

Fagodiya RK, Pathak H, Kumar A, Bhatia A, Jain N (2017) Global temperature change potential of nitrogen use in agriculture: a 50-year assessment. Sci Rep 7:44928

Farooq M, Siddique KH (2015) Conservation agriculture: concepts, brief history, and impacts on agricultural systems. In: Conservation agriculture. Springer, Cham, pp 3–17

Fließbach A, Oberholzer HR, Gunst L, Mäder P (2007) Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agr Ecosyst Environ 118:273–284

Florentín MA, Peñalva M, Calegari A, Derpsch R, McDonald MJ (2010a) Green manure/cover crops and crop rotation in conservation agriculture on small farms. Integr Crop Manage 12:7–12

Fu B, Chen L, Huang H, Qu P, Wei Z (2021) Impacts of crop residues on soil health: a review. Environ Pollutants Bioavail 33(1):164–173

Gałązka A, Niedźwiecki J, Grządziel J, Gawryjołek K (2020) Evaluation of Changes in glomalin-related soil proteins (GRSP) content, microbial diversity and physical properties depending on the type of soil as the important biotic determinants of soil quality. Agronomy 10(9):1279

Golec AFC, Pérez PG, Lokare C (2007) Effective microorganisms: myth or reality? Revista Peruana De Biologia 14(2):315–319

Gómez E, Ferreras L, Toresani S (2006) Soil bacterial functional diversity as influenced by organic amendment application. Biores Technol 97:1484–1489
Gray LC, Morant P (2003) Reconciling indigenous knowledge with scientific assessment of soil fertility changes in southwestern Burkina Faso. Geoderma 111:425–437
Guerrieri MC, Fanfoni E, Fiorini A, Trevisan M, Puglisi E (2020) Isolation and screening of extracellular PGPR from the rhizosphere of tomato plants after long-term reduced tillage and cover crops. Plants 9(5):668
Haynes RJ, Mokolobate MS (2001) Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. Nutr Cycl Agroecosyst 59:47–63
Hedley MJ, Stewart JWB, Chauhan B (1982) Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci Soc Am J 46(5):970–976
Huber S, Syed B, Freudenschuss A, Ernsten V, Loveland P (2001) Proposal for a European soil monitoring and assessment framework. Technical report no. 61, Europe Environmental Agency, Copenhagen, Denmark.
Ibrahim A, Usman ARA, Al-Wabel MI, Nadeem M, Ok YS, Al-Omran A (2017) Effects of conocarpus biochar on hydraulic properties of calcareous sandy soil: influence of particle size and application depth. Arch Agron Soil Sci 63(2):185–197
Ibrahim HM, Al-Wabel MI, Usman AR, Al-Omran A (2013) Effect of Conocarpus biochar application on the hydraulic properties of a sandy loam soil. Soil Sci 178(4):165–173
Iqbal S, Naz T, Abdul Sattar M (2021a) Challenges and opportunities linked with waste management under global perspective: a mini review. J Qual Assur Agric Sci 1(1):9–13
Iqbal, S., Riaz, U., Murtaza, G., Jamil, M., Ahmed, M., Hussain, A. and Abbas, Z. (2021b). Chemical fertilizers, formulation, and their influence on soil health. In: Microbiota biofertilizers. Springer, Cham, pp 1–15
Janeau JL, Bricquet JP, Planchon O, Valentin C (2003) Soil crusting and infiltration on steep slopes in northern Thailand. Eur J Soil Sci 54:543–554
Jarecki MK, Lal R (2003) Crop management for soil carbon sequestration. Crit Rev Plant Sci 22(6):471–502
Jat SL, Parihar CM, Singh AK, Nayak HS, Meena BR, Kumar B, Parihar MD, Jat ML (2019) differential response from nitrogen sources with and without residue management under conservation agriculture on crop yields, water-use and economics in maize-based rotations. Field Crop Res 236:96–110
Jayaraman S, Naorem AK, Sinha NK, Mohanty M, Hati KM, Patra AK, Dalal RC (2021a) conservation agriculture: issues, prospects, and challenges in rainfed regions of India. In: Conservation agriculture: a sustainable approach for soil health and food security. Springer, Singapore, pp 1–21
Jayaraman S, Dang YP, Naorem A, Page KL, Dalal RC (2021b) Conservation agriculture as a system to enhance ecosystem services. Agriculture 11(8):718
Karlen DL (2012) Soil health: the concept, its role, and strategies for monitoring. In: Wall DH, Bardgett RD, Behan-Pelletier V (eds) Soil ecology and ecosystem services. Oxford University Press, Oxford, pp 331–336
Khalifa N, Yousef LF (2015) A A Short Report on changes of quality indicators for a sandy textured soil after treatment with biochar produced from fronds of date palm. Energy Procedia 74:960–965
Kimetu JM, Lehmann J, Ngoze SO, Mugendi DN, Kinyangi JM, Riha S, Pell AN (2008) Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. Ecosystems 11(5):726
Kladivko EJ (2001) Tillage systems and soil ecology. Soil Tillage Res 61(1–2):61–76
Kumar R, Mahajan G, Srivastava S, Sinha A (2014a) Green manuring: a boon for sustainable agriculture and pest management—a review. Agric Rev 35(3):196–206
Kumar R, Srivastava S, Srivastava M, Sinha A (2010) Effects of organic amendments on soil mycoflora. Asian J Plant Pathol 4(2):73–81

Kumar S, Nakajima T, Mbonimpa EG, Gautam S, Somireddy UR, Kadono A, Fausey N (2014b) Long-term tillage and drainage influences on soil organic carbon dynamics, aggregate stability and corn yield. Soil Sci Plant Nutr 60(1):108–118

Kumar V, Jat HS, Sharma PC, Gathala MK, Malik RK, Kamboj BR, McDonald A (2018) Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. Agr Ecosyst Environ 252:132–147

Lakhdar A, Rabhi M, Ghnaya T, Montemurro F, Jedidi N, Abdelly C (2009) Effectiveness of compost use in salt-affected soil. J Hazard Mater 171(1–3):29–37

Laghari M, Mirjat MS, Hu Z, Fazal S, Xiao B, Hu M, Guo D (2015) Effects of biochar application rate on sandy desert soil properties and sorghum growth. CATENA 135:313–320

Lal R, Bouma J, Brevik E, Dawson L, Field DJ, Glaser B, Zhang J (2021) Soils and sustainable development goals of the United Nations (New York, USA): an IUSS perspective. Geoderma Regional e00398

Lal R (2005) world crop residues production and implications of its use as a biofuel. Environ Int 31:575–584

Lee JJ, Park RD, Kim YW, Shim JH, Chae DH, Rim YS, Sohn BK, Kim TH, Kim KY (2004) Effect of food waste compost on microbial population, soil enzyme activity and lettuce growth. Biores Technol 93:21–28

Li Y, Chang SX, Tian L, Zhang Q (2018) Conservation agriculture practices increase soil microbial biomass carbon and nitrogen in agricultural soils: a global meta-analysis. Soil Biol Biochem 121:50–58

Lindsay EC, Metcalfe NB, Llewellyn MS (2020) The potential role of the gut microbiota in shaping host energetics and metabolic rate. J Anim Ecol 89(11):2415–2426

Liu J, Macrae ML, Elliott JA, Baulch HM, Wilson HF, Kleinman PJ (2019) Impacts of cover crops and crop residues on phosphorus losses in cold climates: a review. J Environ Qual 48(4):850–868

Liu X, Xu Y, Engel BA, Sun S, Zhao X, Wu P, Wang Y (2021) The impact of urbanization and aging on food security in developing countries: the view from Northwest China. J Clean Prod 292:126067

Lu XA (2020) Meta-analysis of the effects of crop residue return on crop yields and water use efficiency. PLoS ONE 15:e0231740

Lundekvam HE, Romstad E, Øygarden L (2003) Agricultural policies in Norway and effects on soil erosion. Environ Sci Policy 2003(6):57–67

Malet JP, Auzet AV, Maquaire O, Ambroise B, Descroix L, Esteves M, Vandervaere JP, Truchet E (2003) Soil surface characteristics influence on infiltration in black marls: application to the Super-Sauze earthflow (Southern Alps, France). Earth Surf Proc Land 28:547–564

Maiti P, Panda AK, Ghorai SK (2021) Study of salinity infiltration in soil due to vannamei shrimp farming in the adjoining area of Contai, Purba Medinipur, West Bengal, India and its immediate economic effect

Maneepitak S, Ullah H, Paothong K, Kachenchart B, Datta A, Shrestha RP (2019) Effect of water and rice straw management practices on yield and water productivity of irrigated lowland rice in the central plain of Thailand. Agric Water Manag 211:89–97

Mangalassery S, Kalaivanan D, Philip PS (2019) Effect of inorganic fertilisers and organic amendments on soil aggregation and biochemical characteristics in a weathered tropical soil. Soil Tillage Res 187:144–151

Mangrich AS, Cardoso EMC, Doumer ME, Romão LPC, Vidal M, Rigol A, Novotny EH (2015) Improving the water holding capacity of soils of Northeast Brazil by Biochar augmentation water challenges and solutions on a global scale. Am Chem Soc 1206:339–354

Marinari S, Masciandaro G, Ceccanti B, Grego S (2000) Influence of organic and mineral fertilisers on soil biological and physical properties. Biores Technol 72:9–17

Martín-Lammerding D, Gabriel JL, Zambrana E, Santín-Montanyá I, Tenorio JL (2021) Organic amendment vs. mineral fertilization under minimum tillage: changes in soil nutrients, soil organic matter, biological properties and yield after 10 years. Agriculture 11(8):700

Meena RS, Lal R (2018) Legumes for soil health and sustainable management. Springer, Singapore

Meena RS, Vijayakumar V, Yadav GS, Mitran T (2018) Response and interaction of *Bradyrhizobium japonicum* and arbuscular mycorrhizal fungi in the soybean rhizosphere. Plant Growth Regul 84(2):207–223

Melman DA, Kelly C, Schneekloth J, Calderón F, Fonte SJ (2019) Tillage and residue management drive rapid changes in soil macrofauna communities and soil properties in a semiarid cropping system of Eastern Colorado. Appl Soil Ecol 143:98–106

Melero S, Riuz Porrai JC, Herencia JF, Madejon E (2006) Chemical and biochemical properties in a sylty loam soil under conventional and organic management. Soil Tillage Res 90:162–170

Mendes IC, Sousa DMG, Dantas OD, Lopes AAC, Junior FBR, Oliveira MI, Chaer GM (2021) Soil quality and grain yield: a win–win combination in clayey tropical oxisols. Geoderma 388:114880

Mendoza TC, Mendoza BC (2016) A review of sustainability challenges of biomass for energy, focus in the Philippines. Agric Technol 12:281–310

Mondal M, Garai S, Banerjee H, Sarkar S, Kundu R (2020) Mulching and nitrogen management in peanut cultivation: an evaluation of productivity, energy trade-off, carbon footprint and profitability. Energy Ecol Environ 1–15

Mugwe J, Otieno EO (2021) Integrated soil fertility management approaches for climate change adaptation, mitigation, and enhanced crop productivity

Naresh RK, Gupta RK, Rathore RS, Dwivedil A, Singh HL, Kumar V, Tyagil S (2017) Crop residue management and soil health with changing climate in smallholders farming: a subtropical Indian perspective. Int J Curr Microbiol App Sci 6(2):1591–1609

Natural Resources Conservation Services (NRCS) (2012) Soil health. Available from http://www.nrcs.usda. Gov/wps/portal/nrcs/main/soils/health/. Accessed 20 Jan 2019

Nawaz A, Farooq M (2021) Agricultural practices and sustainable management in South Asia. Life Land 36–48

Nayak JJ, Vaidya AK (2018) Green manure in crop production and soil health. Int J Innovative Research in Science, Engineering and Technology 7(6):7378–7381

Nazir S, Abbasi A, Komal N, Riaz U, Ashraf K, Ahmad N, Agarwal S, Nasir R, Chen Y (2021) Bioresource nutrient recycling in the rice-wheat cropping system: cornerstone of organic agriculture. Plants 10(11):2323

Ntakirutimana L, Li F, Huang X, Wang S, Yin C (2019) Green manure planting incentive measures of local authorities and farmers' perceptions of the utilization of rotation fallow for sustainable agriculture in Guangxi, China. Sustainability 11(10):2723

Ochiai N, Powelson ML, Crowe FJ, Dick RP (2008) Green manure effects on soil quality in relation to suppression of Verticillium wilt of potatoes. Biol Fertil Soils 44(8):1013–1023

Pandey AK, Singh MK (2016) Importance and uses of green manuring in field crops. Rashtriya Krishi 11(2):35–35

Parr JF, Papendick RI (1978) Factors affecting the decomposition of crop residues by microorganisms. Crop Residue Manage Syst 31:101–129

Pieters AJ (1927) Green manuring. Willey, New York

Pimentel D, Hepperly P, Hanson J, Douds D, Seidel R (2005) Environmental, energetic, and economic comparisons of organic and conventional farming systems. Bioscience 55(7):573–582

Purnamasari L, Rostaman T, Widowati LR, Anggria L (2021) Comparison of appropriate cation exchange capacity (CEC) extraction methods for soils from several regions of Indonesia. IOP Conf Ser Earth Environ Sci 648(1):012209. IOP Publishing

Pung H, Aird PL, Cross S (2004) The use of Brassica green manure crops for soil improvement and soil borne disease management. In: 3rd Australian soil borne diseases symposium, February 2004, pp 1–2

Rapport DJ, Regier HA, Hutchinson TC (1985) Ecosystem behavior under stress. Am Nat 125(5):617–640

Rathod PH, Bhoyar SM, Katkar RN, Kadu PR, Jadhao SD, Konde NM, Deshmukh PW, Patle PN (2019) Recycling and management of crop residues for sustainable soil health in climate change scenario with farmer's profit as frontline moto. J Pharmacog Phytochem 51–55

Rayns F, Rosenfeld A (2010) Green manures – effects on soil nutrient management and soil physical and biological properties HDC, Factsheet 24/10, Soil grown crops Projects FV 299 and 299a.
Reicosky DC, Kemper WD, Langdale G, Douglas CL, Rasmussen PE (1995) Soil organic matter changes resulting from tillage and biomass production. J Soil Water Conserv 50(3):253–261
Riaz U, Mehdi SM, Iqbal S, Khalid HI, Qadir AA, Anum W, Ahmad M, Murtaza G (2020) Bio-fertilizers: eco-friendly approach for plant and soil environment. In: Hakeem et al (eds) Bioremediation and biotechnology. Springer Nature, Switzerland
Rigon JPG, Calonego JC, Capuani S, Franzluebbers AJ (2021) Soil organic C affected by dry-season management of no-till soybean crop rotations in the tropics. Plant Soil 462(1):577–590
Roberts SD, Harrington CA, Terry TA (2005) Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability, and Douglas-fir seedling growth. For Ecol Manage 205(1–3):333–350
Ronchi S, Salata S, Arcidiacono A, Piroli E, Montanarella L (2019) Policy instruments for soil protection among the EU member states: a comparative analysis. Land Use Policy 82:763–780
Rusinamhodzi L, van Wijk MT, Corbeels M, Rufino MC, Giller KE (2015) Maize crop residue uses and trade-offs on smallholder crop-livestock farms in Zimbabwe: economic implications of intensification. Agr Ecosyst Environ 214:31–45
Sanchez PA (2002) Soil fertility and hunger in Africa. Science 295:2019–2020
Saria AG, Sibuga KP, Semu E, Jensen HH (2018) Soil fertility dynamics of ultisol as influenced by greengram and mucuna green manures. J Plant Sci Agric Res 2(2):14
Sasal C, Andriulo A, Ullé J, Abrego F, Bueno M (2000) Efecto de diferentes enmiendas sobre algunas propiedades edáficas, en sistemas de producción hortícola del centro norte de la región pampeana. Ciencia Del Suelo 18:95–104
Scherer HW (2000) Fertilizers. In: Ullmann's encyclopedia of industrial chemistry. Wiley-VCH, Weinheim
Schloter M, Dilly O, Munch JC (2003) Indicators for evaluating soil quality. Agr Ecosyst Environ 98:255–262
Schloter M, Munch JC, Tittarelli F (2006) Managing soil quality. In: Bloem J, Hopkins DW, Benedetti A (eds) Microbiological methods for assessing soil quality. CAB International, Wallingford, pp 50–62
Schoenholtz SH, Van Miegroet H, Burger JA (2000) A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. For Ecol Manage 138:335–356
Schröder J (2005) Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. Biores Technol 96(2):253–326
Schumann RA, Meyer JH, Van Antwerpen R (2000) A review of green manuring practices in sugarcane production. Proc South Afr Sugarcane Technol Assess 74:93–100
Selvi RV, Kalpana R (2009) Potentials of green manure in integrated nutrient management for rice: a review. Agric Rev 30(1):40–47
Shafer SR, Karlen DL, Tracy PW, Morgan CL, Honeycutt CW (2021) Laboratory methods for soil health assessment: an overview. Laboratory Methods Soil Health Anal 2:1
Shukla MK, Lal R, Ebinger M (2006) Determining soil quality indicators by factor analysis. Soil Tillage Research 87(2):194–204
Sinha A, Kumar R, Kamil D, Kapur P (2009) Release of nitrogen, phosphorus and potassium from decomposing *Crotalaria juncea* L. in relation to different climatic factors. Environ Ecol 27(4B):2077–2081
Six J, Elliot ET, Paustian K (2000) Soil structure and soil organic matter: II. A normalized stability index and the effect of mineralogy. Soil Sci Soc Am J 64:1042–1049
Smith P, Powlson DS, Smith JU, Falloon P, Coleman K (2000) Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Glob Change Biol 6:525–539
Srinivasarao CH, Venkateswarlu B, Lal R, Singh AK, Sumanta K (2013) Sustainable management of soils of dryland ecosystems for enhancing agronomic productivity and sequestering carbon. Adv Agron 121:253–329

Sulieman S, Tran L-SP (2014) Symbiotic nitrogen fixation in legume nodules: metabolism and regulatory mechanisms. Int J Mol Sci 15:19389–19393

Sulieman S, Tran L (2016) Legume nitrogen fixation in a changing environment. Springer, Cham

Talgre L, Lauringson E, Roostalu H, Astover A, Makke A (2012) Green manure as a nutrient source for succeeding crops. Plant Soil Environ 58(6):275–281

Tejada M, Gonzalez JL, García-Martínez AM, Parrado J (2008a) Application of a green manure and green manure composted with beet vinasse on soil restoration: effects on soil properties. Biores Technol 99(11):4949–4957

Tejada M, Gonzalez JL (2003) Effects of the application of a compost originating from crushed cotton gin residues on wheat yield under dryland conditions. Eur J Agron 19:357–368

Tejada M, Gonzalez JL, García-Martínez AM, Parrado J (2008b) Application of a green manure and green manure composted with beet vinasse on soil restoration: effects on soil properties. Soil Res 99(11):4949–4957

Tejada M, González JL, García-Martínez AM, Parrado J (2008c) Application of a green manure and green manure composted with beet vinasse on soil restoration: effects on soil properties. Biores Technol 99:4949–4957

Thiele-Bruhn S, Schloter M, Wilke BM, Beaudette LA, Martin-Laurent F, Cheviron N, Römbke J (2020) Identification of new microbial functional standards for soil quality assessment. Soil 6(1):17–34

Tóth, G. E. (2008). Soil Quality in the European Union. In: TÓTH, G., MONTANARELLA, L. and RUSCO, E. (Eds.), JRC Scientific and Technical Reports. Threats to Soil Quality in Europe, 11–19.

Tóth G, Stolbovoy V, Montanarella L (2007) Soil Quality and sustainability evaluation—an integrated approach to support soil-related policies of the European Union. EUR 22721 EN. 40 p. Office for Official Publications of the European Communities, Luxemburg ISBN, 987-92-79-05250-7

Treonis AM, Austin EE, Buyer JS, Maul JE, Spicer L, Zasada IA (2010) Effects of organic amendment and tillage on soil microorganisms and microfauna. Appl Soil Ecol 46:103–110

Turmel MS, Speratti A, Baudron F, Verhulst N, Govaerts B (2015) Crop residue management and soil health: a systems analysis. Agric Syst 134:6–16

Vanzolini JI, Galantini JA, Martínez JM, Suñer L (2017) Changes in soil pH and phosphorus availability during decomposition of cover crop residues. Arch. Agron. Soil Sci. 63(13):1864–1874

Velmourougane K, Blaise D (2017) Soil health, crop productivity and sustainability challenges. In: Sustainability challenges in the agrofood sector. Wiley, Chichester, pp 509–531

Wang LK, Wang MHS, Hung YT (2021) Integrated natural resources research. Springer, Berlin, pp 569–629

Webster KL, Hazlett PW, Brand G, Nelson SA, Primavera MJ, Weldon TP (2021) The effect of boreal jack pine harvest residue retention on soil environment and processes. For Ecol Manage 497:119517

Xia X, Zhang P, He L, Gao X, Li W, Zhou Y, Yang L (2019) Effects of tillage managements and maize straw returning on soil microbiome using 16S rDNA sequencing. J Integr Plant Biol 61(6):765–777

Xie Z, Tu S, Shah F, Xu C, Chen J, Han D, Liu G, Li H, Muhammad I, Cao W (2016) Substitution of fertilizer-N by green manure improves the sustainability of yield in double-rice cropping system in south China. Field Crop Res 188:142–149

Xu JM, Tang C, Chen ZL (2006) The role of plant residues in pH change of acid soils differing in initial pH. Soil Biol Biochem 38(4):709–719

Yadav GS, Lal R, Meena R, Babu S, Das A, Bhoumik SN, Datta M, Layak J, Saha P (2019) Conservation tillage and nutrient management effects on productivity and soil carbon sequestration under double cropping of rice in North Eastern Region of India. Ecol Ind 105:303–315

Yadav D, Vishwakarma AK, Sharma NK, Biswas AK, Ojasvi PR, Kumar D, Singh D (2021) Sustaining the properties of black soil in Central India through crop residue management in a conservation-agriculture-based soybean–wheat system. Land Degrad Dev 32(10):2906–2921
Yang L, Bai J, Liu J, Zeng N, Cao W (2018) Green manuring effect on changes of soil nitrogen fractions, maize growth, and nutrient uptake. Agronomy 8:261
Ye X, Liu H, Li Z, Wang Y, Wang Y, Wang H, Liu G (2014) Effects of green manure continuous application on soil microbial biomass and enzyme activity. J Plant Nutr 37(4):498–508
Zaccheo PVC, Neves CSVJ, de Cinque Mariano D, Zorzenoni TO, Higashibara LR, Piccinin GG, Okumura RS (2016) Green manure in fruit culture: aspects on soil quality and use in agriculture. Afr J Agric Res 11(17):146
Zalidis G, Stamatiadis S, Takavakoglou V, Eskridge K, Misopolinos N (2002) Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology. Agr Ecosyst Environ 88:137–146
Zaman S, Pramanick P, Mitra A (2019) Chemical fertilizer, Department of Marine Science, University of Calcutta, Kolkata, India
Zhao X, Liu BY, Liu SL, Qi J, Wang X, Pu C, Li S, Zhang X, Yang X, Lal R (2020) Sustaining crop production in China's cropland by crop residue retention: a meta-analysis. Land Degr Develop 31:694–709
Zhu L, Tang Y, Weng Y, Huang K, Wang J, Zhao J, Wu L (2021) Effects of burning harvested residues on the archaeal and bacterial communities of *Eucalyptus urophylla* substituting native vegetation. Appl Soil Ecol 158:103796

Saba Nazir has completed her BS and M. Phil from the Department of Environmental Sciences, University of Lahore, Pakistan. She has expertise in judicious use of wastewater to grow crops that will help solve water scarcity issue in the agriculture sector and use of bioresources for sustainable crop production under a changing climatic scenario. She published research papers and book chapters at national and international levels.

Dr. Qamar uz Zaman is a young environmentalist working as an Assistant Professor in the Department of Environmental Sciences at the University of Lahore (UOL). He obtained his B.Sc. (Hons.), M.Sc. (Hons.) and Ph.D. in Plant Sciences/Agronomy from the University of Agriculture, Faisalabad, Punjab, Pakistan. He has a good record of publications and experience, working on different projects to put his proper share in developing advanced technologies for students. His major areas of his research are sustainability issues in environment and agriculture with major focus on zinc and iron biofortification under a changing climate scenario, heavy metal toxicity in the cereals and vegetables, abiotic stresses and soil microflora (bacteria, fungi and algae).

Dr. Abdulrasoul Al-Omran is currently working as a Professor of soil and water sciences. He obtained his Ph.D. degree in 1984 from Oregon State University, Corvallis, USA in Soil Science and a M.Sc. from University of California at Davis, USA in 1979 in Water Science (Irrigation). He is serving as Editor-in-chief of Saudi Journal of Agricultural Sciences. His major field of interest is Soil Science (soil physics) and Agricultural Engineering. He published 90 articles in national and international journals and 4 books. He is also a member of the American Society of Agronomy, the Soil Science Society of America and the Saudi Society for Agricultural Science.

Dr. Jan W. Hopmans is currently working as a Professor at the Department of Land, Air and Water Resources, Hydrology Program University of California Davis. He obtained his Ph.D. degree in 1985 from Auburn University, in Soil Physics. His major field of interest is soil physics, flow and transport modeling, soil moisture, microtomography, scaling techniques, plant root-soil water interactions, parameter optimization, soil hydraulic properties, climate change impacts, irrigation water management, soil moisture sensor development, soil salinity, and forest hydrology.

He published 308 articles in national and international journals and 4 Books. He is also an Honorary Professor at the China Agricultural University since 2019.

Kamran Ashraf is currently working as a Lecturer at the Department of Food Sciences, Government College University Faisalabad, Sahiwal Campus. He has two years of teaching and research experience, which include working as a Lecturer in Comsats University, Islamabad, Sahiwal Campus and University of Montgomery, Sahiwal, Pakistan. He is also serving as a Secretary Press and Public Relations in Pakistan Society of Food Scientists and Technologists. Kamran's research background is linked with multigrain products and their nutritional aspects. His major areas of research are antioxidant potential of multigrain products and their beneficial aspects and sustainability issues in environment and agriculture, with major focus on beneficial elements for heavy metal toxicity in the cereals and vegetables.

Nayab Komal is young, hardworking and dedicated environmentalist. She has completed her M. Phil from the Department of Environmental Sciences, The University of Lahore, Pakistan in 2021. She has experience in working with projects delivery teams and environmental engineering firms and in the role of agroforestry in climate change mitigation. She published research articles in national and international journals. She is interested to further explore the role of forest, especially agroforests and plantations in climate change mitigation by using some models and advance techniques.

Managing the Soil Erosion Through the Use of Polyacrylamide: An Empirical Study

Balqees Aldabbagh, Jabbar Briahi Auda, Hanaa Alesa, N. Adnan, and O. Hmaizah

Abstract Polyacrylamide (PAM) is a water-soluble polymer used to bind soil particles together for gaining stability against water and wind erosion. It is highly water-absorbent. This chapter aims to study the PAM properties like thermal degradation and melting point by Differential Scanning Calorimetry (DSC). Surface parameters like roughness, bearing index, core fluid retention index, and Valley fluid retention index were determined by atomic force microscopy. Surface runoff for soil stability also was determined under different conditions by using a spray gun. Weight loss also was tested for soil stability conclusion. Soil samples were prepared by mixing 25% of sandy soils with 75% clay soil. The molds were prepared with a dimension of (1 m * 75 cm * 10 cm) for four samples and sprayed with different concentrations of PAM that dissolved in water with different concentrations including (25, 35, and 45) % and left for 24 h for drying of samples. Samples were subjected to artificial rainfall for 12 h after being placed at a 10° angle to increase the rate of erosion. Results prove that the surface runoff and the weight loss of soil decrease with the increase of polyacrylamide concentration.

Keywords Soil stability · Polyacrylamide · Surface runoff · Soil loss

1 Introduction

Soil erosion is sorely a challenge affecting the sustainability and productivity of agriculture, thus leading to economic loss (Pimentel et al. 1995). Terrestrial heating leads to significant changes in the weather and environment. In addition, short but intensive storms during summer are one of the main factors which lead to soil erosion

B. Aldabbagh
Applied, Science Department, University of Technology, Baghdad, Iraq

J. B. Auda · H. Alesa (✉) · N. Adnan · O. Hmaizah
College of Materials Engineering, University of Babylon, Babylon, Iraq
e-mail: mat.hanua.jawad@uobabylon.edu.iq

N. Adnan
e-mail: Mat.nardeen.albakry@uobabylon.edu.iq

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*,
https://doi.org/10.1007/978-3-031-12586-7_24

(Fischer and Knutti 2015). The raise in the number of extreme events has been specified at both territorial and global scales (Perkins et al. 2012; Rahmstorf and Coumou 2012). For example, a dense storm happened in 2017 in northwest Loess Plateau, Sweden County, led to huge ruin and economic losses. Thus, there is a need to develop practices to counter soil erosion while preserving agriculture from its impacts through for instance coating by yields or herbs and geotextiles (Cerda et al. 2016; Prosdocimi et al. 2016). Within this perspective, polyacrylamide (PAM) is one of the polymers that used to protect the soil by covering it with a layer of water-soluble polymer. This polymer controls the soil erosion by collecting the soil particles and preventing them from drifting under critical weather conditions such as heavy rain and torrents. It also effectively acts as a layer against mold and algae harmful to the soil, helps preserve the natural properties of the soil, and prevents the accumulation of harmful salts or germs, which leads to damage after the floods (Ajwa and Trout 2006).

The fact that soil erosion is actually a worldwide threat, its management is more than necessary. The activity of the PAM has been studied for erosion control in moderate ambient conditions. In equatorial regions, however, ambient conditions are ordinarily harsh and few studies have been performed; Brazilian region is a good example.

Alexandre and Steven (2010) studied the PAM effect for soil erosion control in Brazil. They found that the use of PAM to limit soil erosion in Brazilian may be a perfect option to decrease the effect of the soil erosion process, but additional research is needed to enhance its application.

Shaojuan et al. (2018) studied the effect of PAM and polysaccharide (Jag C 162) on soil erosion. These polymers were applied to erosion in regions filled with less soil (inclined at 20°) with four concentrations for each polymer. The treated erosion plots were then offered to two simulated rainfall proceeding (dry and wet run) to explore their effectiveness and durability in controlling soil erosion. Both simulated rainfall events were at an intensity of 120 mm/h and continued for 30 min with 24 h of free discharge in between. They concluded that both polymers could reduce runoff effectively, control plate erosion, in addition to enhancing soil collection due to their ability to bind and stabilize the soil particles.

Birhanu et al. (2020) tested the effect of PAM on reducing surface runoff of soil under consecutive rain. The effective granular size of PAM in reducing soil loss was determined. The effectiveness of PAM was tested by applying it with a mixture of lime or gypsum at different rates. The authors concluded that P20 is the best test for limiting surface runoff of soil.

2 Experimental Part

2.1 Materials

Polyacrylamide with formula $(C_3H_5NO)n$ as a white powder with 200 mesh dimensional, 1.1 g/cm^3 density, is a biomaterial and has hydrophilic property. Mw 5,000,000 from SIGMA Aldrich Company, in addition to tap water as a solvent of polyacrylamide, were used as a main covering material of this research. Sandy soil from sandbank of Al-Habania beach in Al Ramadi City, Iraq, was provided, in addition to clay soil from natural Iraqi soil which was used for preparation of the soil samples.

Wood molds with dimensions (100 * 75 * 10) cm^3 of (length * width * thickness) were prepared with some very small bores in the base of these molds.

2.2 Preparation of Samples

These soil samples were dehydrated by hot air and sifted into 8 mm groups, then casted to molds, and left for 24 h for drying before testing.

3 Results and Discussion

3.1 Thermal Analysis by DSC of PAM

Figure 1 and Table 1 show the thermal properties of pure polyacrylamide and polyacrylamide with clay that used in this research.

We observed that thermal properties of PAM increased after covering it with clay. This is due to the high thermal insulation of clay, which leads to more stability at special conditions such as high temperature days (Carola and Mariaenrica 2012).

3.2 Surface Morphology of PAM and PAM + Clay

Figure 2 and Table 2 show the surface morphology of samples:

We observe that the higher concentration of polymers (about 45% PAM) leads to highest roughness of surface; this refers to higher aggregation of soil molecules and higher bearing index with highest polymer concentration, which leads to higher protection of soil under weathering conditions (Allison et al. 2003).

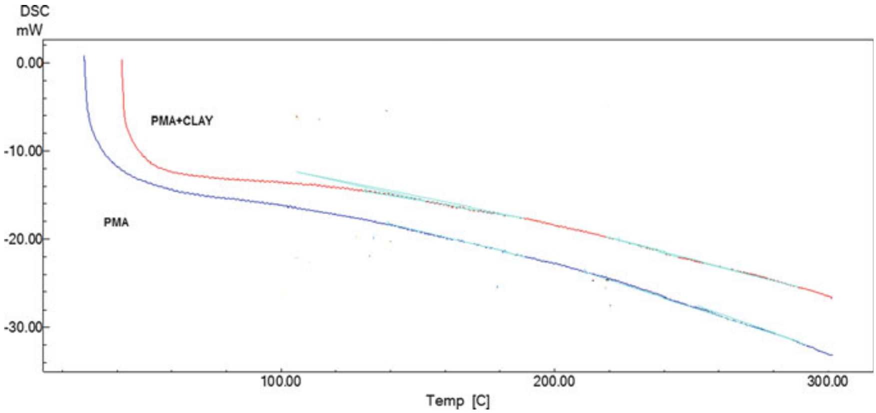


Fig. 1 DSC analysis of PAM and PAM + clay

Table 1 Thermal analysis of PAM and PAM + clay by DSC

Sample	Tm (°C)	Endset (°C)	Onset (°C)
polyacrylamide (pure)	223	107	135
Polyacrylamide + Clay	245	205	159

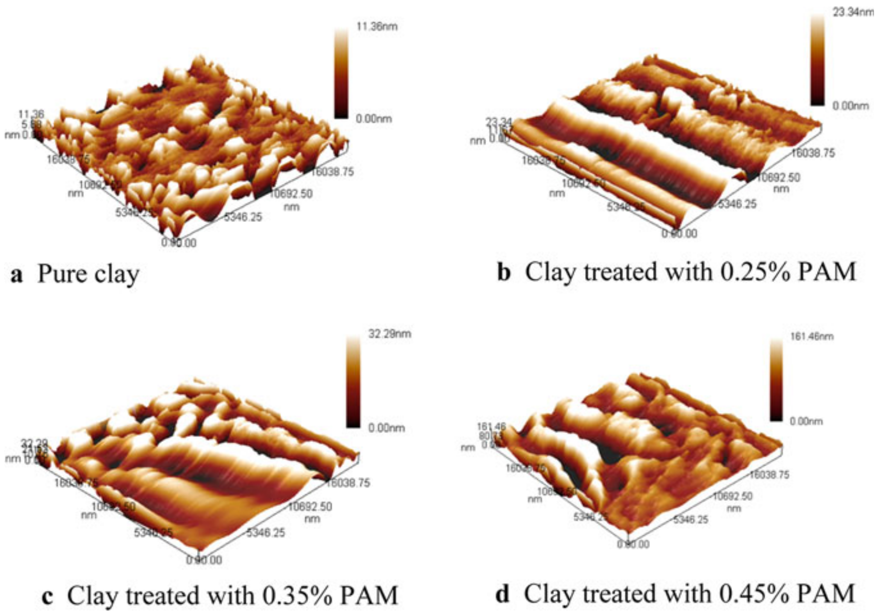


Fig. 2 Surface morphology by 3-dimensions AFM images of samples: **a** without treatment, **b** 0.25% Con. PAM, **c** 35% Con. PAM, and **d** 45% Con. PAM

Table 2 Surface parameters of samples by AFM tested

Sample No	Sample	Roughness average nm	Core fluid retention index	Valley fluid retention index	Bearing index
1	Pure clay	2.29	1.53	0.129	2.03
2	1 + 0.25% PAM	5.98	1.52	0.057	2.15
3	1 + 0.35% PAM	8.36	1.57	0.0342	3.14
4	1 + 0.45% PAM	33	1.51	0.128	3.43

3.3 Soil Loss

Table 3 and Fig. 3 show the soil loss of samples treated via different concentration of PAM under rainwater.

We notice from Fig. 3 that the soil erosion of samples without treatment by polymer solution spray attains the highest value (about 0.254), while the treated sample (45% con.) has the lowest value of soil loss (about 0.097). This means that the decrease

Table 3 Weight loss of soil samples treated with different concentrations of PAM under water spray

Sample No	Molds dimensions cm^3	Sample weight g	Concentrations of (PAM) %	Soil loss under 0.5 L	Soil loss under 0.75 L
1	50 * 50 * 5	400	0.0	0.254	0.254
2	50 * 50 * 5	400	25	0.155	0.143
3	50 * 50 * 5	400	35	0.124	0.110
4	50 * 50 * 5	400	45	0.097	0.025

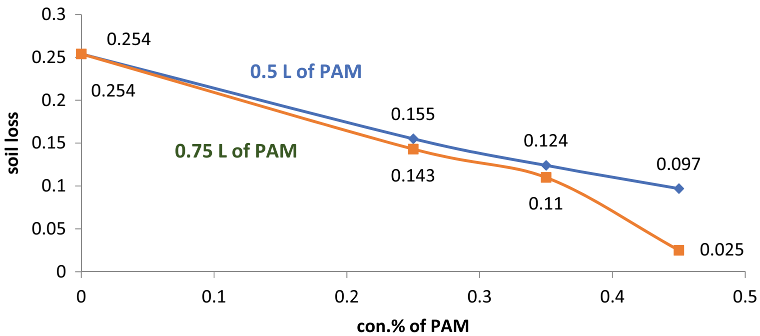


Fig. 3 Soil loss of samples treated with different concentration of PAM under run spray

of soil erosion is the result of the increase of treatment by polymer concentration; this can be explained by the growing aggregation and bonding of soil molecules via polymer solution. On the other hand, the soil erosion of samples decreases with the increase of the quantity of polymer solution from 0.5 to 0.75 L (Mamedov et al. 2009; Shaojuan et al. 2018; Chen et al. 2016).

4 Conclusion

We can conclude that the polyacrylamide dissolved in water with 45% concentration leads to highest protection of soil and results in the lowest soil erosion under rain day. Also, the soil loss decreases with the increase of the protection layer through the spray of a growing quantity of polymer solution (from 0.5 to 0.75 L).

Acknowledgements We would like to express our deepest appreciation to all those who provided us with the needed support to complete this research.

References

Ajwa HA, Trout TJ (2006) Polyacrylamide and water quality effects on infiltration in sandy loam soils. Soil Sci Soc Am J 70:643–650

Alexandre S, Steven F (2010) Potential use of polyacrylamide for soil erosion control in Brazil. J Sustain Dev 3(4):109–117

Allison YS, Andreas A, Thomas F (2003) Detailed surface roughness characterization of engineering surfaces undergoing tribological testing leading to scuffing. Wear 255:556–568

Birhanu K, Atsushi T, Nigussie H, Amrakh I, Mitsuru T, Ayele A, Derege T, Tsugiyuki M, Enyew A, Getu A, Mulatu L (2020) Effectiveness of poly acrylamide in reducing runoff and soil loss under consecutive rainfall storms. Sustainability 12:1597

Cerda A, Gonzalez-Pelayo O, Gimenez-Morera A, Jordan A, Pereira P, Novara A, Brevik EC, Prosdocimi M, Mahmoodabadi M, Keesstra S (2016) The use of barley straw residues to avoid high erosion and runoff rates on persimmon plantations in eastern Spain under low frequency high magnitude simulated rainfall events. Soil Res 54:154–165

Carola E, Mariaenrica F (2012) Characterization of nanocomposites by thermal analysis. Materials 5:2960–2980

Chen Z, Chen W, Li C, Pu Y, Sun H (2016) Effects of polyacrylamide on soil erosion and nutrient losses from substrate material in steep rocky slope stabilization projects. Sci Total Environ 554–555:26–33

Fischer EM, Knutti R (2015) Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. Nat Clim Chang 5:560–564

Mamedov AI, Shainberg I, Wagner LE, Warrington DN, Levy GJ (2009) Infiltration and erosion in soils treated with dry PAM, of two molecular weights, and phosphogypsum. Aust J Soil Res 47(8):788

Perkins SE, Alexander LV, Nairn JR (2012) Increasing frequency, intensity and duration of observed global heat waves and warm spells. Geophys Res Lett 39:L20714

Prosdocimi M, Jordán A, Tarolli P, Keesstra S, Novara A, Cerdà A (2016) The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci Total Environ 547:323–330

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R (1995) Environmental and economic costs of soil erosion and conservation benefits. Science 267(5201):1117–1123

Rahmstorf S, Coumou D (2012) Increase of extreme events in a warming world. PNAS 109(12):4708

Shaojuan L, Zhanli W, Yaxian H, Baoyuan L, Jun'e L. (2018) Effectiveness and durability of polyacrylamide (PAM) and polysaccharide (Jag C 162) in reducing soil erosion under simulated rainfalls. Water 10:257

Balqees Aldabbagh is a Professor at the University of Technology, Department of applied Sciences, Materials Science Branch, Iraq. He has supervised 40 Master theses, 18 Ph.D. theses, and more than 15 B.Sc. projects. He also has supervised M.Sc. and Ph.D. theses from other universities (Anbar, Babylon, Tikreet). He has participated in many national and international conferences. He is a member in the team of organization between the Ministry of Higher Education, scientific research institutes, and the Ministry of Industry. He is member in many scientific journals, including: the Engineering and Technology Journal from 2014 at present; Iraqi Science Journal, Baghdad Iniversity from 2012 at present; Basic Education Journal, Almustansirya University from 2014 at present. He is a well a scientific referee for many scientific journals in Iraq.

Jabbar Briahi Auda is Assistant Professor and faculty member at the Department of Polymer and Petrochemical Industries, College of Materials Engineering, University of Babylon, Iraq. His areas of research include composite materials, biopolymers, implants, prosthetic materials and petroleum industries. He has more than 20 published papers and has two patents in the field of composite materials. Dr. Auda is a member of Iraqi union of Engineers, Iraqi Society of Polymers, and Iraqi Society of Nanotechnology.

Postface

Climate change impacts both ecological and food systems through multiple pathways with direct and indirect implications for biodiversity and food security. This has been asserted with high certainty by recent global assessments undertaken by the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the Food and Agriculture Organization (FAO). In addition, the Anthropocene era is witnessing the crossing of the key planetary boundaries that keep us within a safe zone of survival and harmony.

Today, the world is facing increased demand for ecosystem services and food. While the human society has made significant achievements in science, technology, and organization, it is still facing challenges threatening human survival. For example, checking climate change and loss of biodiversity and enhancing food and health security in a sustainable and resilient way are still significant challenges.

Although climate change is seen as a direct risk to social–ecological systems, terrestrial and marine biodiversity loss and unsustainable agriculture are silent threats that are slowly transforming ecosystems and challenging the livelihoods of millions. Most environmental issues have become global concerns and will start impacting each other through various pathways in the future. This evolution should be increasingly addressed by both research and policy.

In such a perspective, this book attempts to capture the links, synergies, and trade-offs among food security, biodiversity, and climate change as a step ahead in understanding the complex interlinkages in social–ecological systems. Studying and presenting the nexus is, however, challenging due to missing links and multiple sub-nexuses that operate at economic, environmental, and societal levels. Such challenges were tackled by the authors, focusing on one nexus at a time and presenting its implications. This increased the extant nexuses covered in this book, from the links between climate and biodiversity to pests, pollinators, and food security. Many chapters covered the importance of traditional and local knowledge, local health baskets, and traditional healing.

M. Behnassi et al. (eds.), *The Food Security, Biodiversity, and Climate Nexus*, https://doi.org/10.1007/978-3-031-12586-7

The book equally focuses on the solutions side, covering the relevance of crop diversification, sustainably managing forests, protected areas network, community engagement, mitigation technologies, and ecosystem restoration. One of the challenges that comes clear from this publication is the huge science-policy-practice gap. The need to link up different environmental and social issues and mainstreaming environment into development strategies could be a solution. But, that requires high coherence at governance levels. Continuing to focus on policies and practices that held true 10–20 years back will hold up transformation both at local and global levels.

Therefore, focusing on sustainability and resilience, this book provides a pathway to understanding nexus approaches to build upon transformative change strategies. Since this book has been compiled at a time when such nexuses are being recognized at a global level, we hope it will contribute to ongoing work, including the IPBES nexus assessment, which is currently underway.

Mohamed Behnassi
Himangana Gupta
Mirza Barjees Baig
Ijaz Rasool Noorka