Manoj Kumar Jhariya · Arnab Banerjee
Ram Swaroop Meena
Dhiraj Kumar Yadav *Editors*

Sustainable Agriculture, Forest and Environmental Management

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Preface

Existence of life on the earth primarily depends upon the agriculture, forest, and environment. Climate change is imposing multifaceted challenges in front of human civilization, food crisis, poverty, and eco-friendly development. It also influences the agroecosystem services through climatic irregularities that are essential for agricultural productivity. The Food and Agriculture Organization (FAO) plays key role in promoting research and developmental activities in various sectors to achieve the Sustainable Development Goals under 2030 Agenda (FAO 2016). The optimum quality food helps to combat climate change through lesser *greenhouse gas* (GHG) emission (0.6 PgC/year). More than 75 years of phasing out of chlorofluorocarbons (CFCs) have been estimated to bring $1.8 trillion net health benefit globally along with prevention of loss worth $460 billion for natural resources. Modern agriculture practice and technologies lead to higher productivity with destruction of agricultural habitat leading to soil-water-air pollution. This has necessitated the development of eco-friendly practices in the agricultural system. Global forests cover accounts for 30% of the total land area on the earth's surface (approx. 4 billion hectares). One fourth of the human population directly or indirectly depends upon the forest resources. Forest simultaneously supports biodiversity as well as helps to combat the global phenomenon of climate change. The growing human population along with the growing human needs has put this valuable resource into question of existence.

As per the UN Strategic Plan for Forests 2017–2030 (UNSPF), an initiative throughout the world has taken for sustainable management of forests in order to check deforestation and its subsequent environment degradation (UN 2017). It includes issues such as sustainable management of forests, combating desertification, reducing land degradation, preventing biodiversity loss, etc. Accordingly, UN (United Nations) general assembly has declared 21st of March to be celebrated as International Day of Forests throughout the world. The motto behind such programs includes increasing forest cover up to 3% worldwide, promoting different afforestation and reforestation schemes by 2020, giving stress upon livelihood security of forest dwellers, etc. A global network through establishment of interrelated networking system needs to be developed between UNFCCC (The United Nations Framework Convention on Climate Change), CBD (*Convention on Biological Diversity*), and UNCCD (The United Nations Convention to Combat Desertification) for worldwide protection of forests. Sustainable forest management practices need to be implemented immediately. The present book aims to address these issues related to forestry and their future implications.

Environment is itself a scare resource nowadays due to human alteration of the habitat. Environment is being degraded in various ways with gradual growth and development of the technology in the modern era of science. Environmental management is a broad term which encompasses pollution prevention, inhibition of environmental degradation, restoration of degraded habitat, and maintaining overall integrity of ecosystem. It is an integrated approach which encompasses food security, poverty alleviation, social justice, healthy environment, and well-being of the people. Pollution reduction is a major challenge from environmental perspectives for human civilization. It has been observed that, globally, net economic gain appears to be $2.5 trillion per annum, or 4% of global GDP (gross domestic product) through phasing out lead from gasoline. In this context, Vienna Convention and Montreal Protocol (VCMP) have successfully phased out more than 90 ozone-depleting substances. As a consequence, incidences such as eye cataracts, skin cancer, and other allied diseases would be reduced to a considerable extent up to 2030 (UNEP 2015). Eco-friendly technologies can reduce different pollutants causing global warming up to 0.5 °C along with saving the lives of more than two million people from climatic hazards till 2030. Recently, during the Bonn Convention held in Germany (2017), special emphasis has been given to ecological restoration of vegetation in riverside and other fringe areas of river. Such approach would therefore promote sustainable development of surface water system on earth. This would benefit mostly the agriculture in terms of irrigation practice as well as help to maintain the ecological integrity of forest ecosystem.

This book would be a valuable asset for teachers, researchers, policy-makers, and undergraduate and graduate students of agriculture, forestry, ecology, soil science, and environmental sciences. Highly professional and internationally renowned researchers have contributed toward cutting-edge scientific information on a broad range of topics covering agriculture, forestry, and environment. The present book focuses on current developments in the field of sustainable agriculture, forestry, and environment which aims toward all-round development of this naturally build ecosystem. Therefore, sustainable agriculture, forest management, and eco-friendly practices are the need of the hour. The objectives of this book are (1) to develop sustainable agricultural practices keeping harmony between agricultural productivity and soil health; (2) to understand the present scenario of forest resource from global perspective and to identify the key aspects for forest protection, conservation, and management; and (3) to understand the various problems of environment degradation and its subsequent remedy and management. This is much important from modern perspectives. Agriculture, forestry, and environment are very much interrelated to each other. The existence of one is not possible without the other. Current updates in the form of sustainable agriculture, forestry, and maintaining ecological integrity by eco-friendly practices are essential for the blissful existence of human civilization. Recent approaches aiming toward sustainable development in the form of eco-friendly farming system, forest conservation, and environment protection, along with implementation of greener and cleaner technologies, need to be identified, prioritized, and implemented through research and development works.

The present book comprises of 16 chapters from eminent experts of various disciplines across the world. The experts are actively engaged in research and developmental activity related to sustainability approach in agriculture, forestry, and environment sector. The present book addresses various sustainability approaches and presents research context in the field of agriculture, forestry, and environment. In the chapters, problems, prospects, and possibilities of the future have been discussed thoroughly both at international and national levels. The issues of changing climate and its mitigation strategies have been widely explored in various chapters. The bioclimatic application, cultivation techniques, abiotic stresses for agricultural crops under changing climate, maintaining soil and water sustainability through ecosystem management, and major issues are covered in the book. Under forestry section, the role of forestry under changing climate has been widely addressed. Specific technologies in the form of short-rotation forestry, agroforestry, as well as multiple utilizations of bamboo species and ecological role of tree outside forests have been illustrated in various chapters. In the environmental management section, inceptions were made through addressing strategies for combating the climate change. Newer issues such as radioecology and its interaction with the environment, pit lake biography, and their potential role toward environmental sustainability have been widely addressed. Further addressing environmental management, the potential role of microorganism in waste management sector as well as phytoremediation approaches has also been addressed.

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Manoj Kumar Jhariya is an assistant professor in the Department of Farm Forestry at Sarguja University, Ambikapur (Chhattisgarh), India, and is the author or coauthor of more than 60 research papers in peer-reviewed journals, 4 books, 20 book chapters, and several extension articles. Dr. Jhariya obtained BSc (Agriculture), MSc (Forestry), and PhD (Forestry) from Indira Gandhi Krishi Vishwavidyalaya (IGKVV), Raipur, Chhattisgarh, India. He was awarded University Gold Medal for securing first class first position in PhD, Chhattisgarh Young Scientist Award in the year 2013 from Chhattisgarh Council of Science and Technology, and a University Grants Commission-Rajiv Gandhi National Fellowship (UGC-RGNF), New Delhi, India. He is editorial board member of several journals and life member in the Indian Science Congress Association, Applied and Natural Science Foundation, Society for Advancement of Human and Nature, Medicinal and Aromatic Plants Association of India, and International Society for Development and Sustainability. He has supervised 41 MSc (Farm Forestry) students and dynamically involved in teaching (postgraduate) and research.

Arnab Banerjee is an assistant professor, Department of Environmental Science, Sarguja Vishwavidyalaya, Ambikapur, Chhattisgarh, India. He has completed MSc and PhD (Environmental Science) from Burdwan University and MPhil in Environmental Science from Kalyani University, West Bengal. He won the University Gold Medal for securing first class first position in MSc examination. He has been awarded Young Scientist Award for best oral presentation at the international conference held at the University of Burdwan. He was a project fellow under UGC-sponsored major research project. To his credit, he has published 65 research papers in reputed national and international journals, 5 books, and 5 book chapters. He is life member of the Academy of Environmental Biology. He has supervised 23 postgraduate students and engaged in postgraduate teaching and research.

Ram Swaroop Meena was born in a farmer family in VOP, Harsana, Tehsil, Laxmangarh, Alwar District, Rajasthan, India. Dr. Meena had his schooling in the same village and graduated in Agriculture in 2003 from the Sri Karan Narendra Agriculture University, Jobner, Jaipur (Rajasthan). Dr. Meena has obtained his Master's and Doctorate in Agronomy from the Swami Keshwanand Rajasthan Agricultural University, Bikaner (Rajasthan), securing first division in all the classes, Junior Research Fellowship (JRF), and Senior Research Fellowship (SRF) from the Indian Council of Agricultural Research, and RGNF Award from the University Grants Commission, Government of India (UGC, GOI). Dr. Meena has been awarded Raman Research Fellowship by the Ministry of Human Resource Development (MHRD), GOI. He has completed his postdoctoral research on soil carbon sequestration under Prof. Rattan Lal, distinguished scientist and director, Carbon Management and Sequestration Center (CMASC), Ohio State University, USA. He is working on soil sustainability, crop productivity, and resources use efficiency, under current climatic era. Dr. Meena has supervised 17 postgraduate and 4 PhD students, and he has 8 years research and teaching experience at undergraduate/postgraduate/PhD level. He is working on the three externally funded running projects including the Department of Science and Technology

(DST), GOI, and involved in many academic and administrative activities going on at the institute/university level. Dr. Meena has published more than 100 research and review papers in peer-reviewed reputed journals and contributed in the edited books with 25 book chapters at national and international levels. He has published three books on the national level and another three on the international level. He has worked as an expert in the National Council of Educational Research and Training (NCERT), MHRD, GOI, to develop the two books for school education at XI and XII standards. Dr. Meena has been awarded several awards, namely, Young Scientist, Young Faculty, Global Research, Excellence in Research, Honorable Faculty Award, etc. Dr. Meena is a member of 9 reputed national and international societies and is working as a general secretary, editor, and member of the editorial board in 12 national and international peer-reviewed reputed journals and attended several national and international conferences in the country and abroad. Dr. Meena is contributing to the agricultural extension activities on farmers' level as associate coordinator in trainings, meetings, workshops, and farmers' fair.

Dhiraj Kumar Yadav is an assistant professor and head, Department of Farm Forestry, Sarguja Vishwavidyalaya, Ambikapur, Chhattisgarh, India. He completed graduation, postgraduation, and PhD in Forestry from Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), IGKVV, and Kumaun University, Nainital, respectively. He has pursued MBA in Human Resource Management from Sikkim Manipal University and Diploma in Environmental Management. He has been awarded Chhattisgarh Young Scientist Award in the year 2008 from Chhattisgarh Council of Science and Technology. He received a merit scholarship during BSc curriculum. He also worked as JRF, SRF, research assistant (RA), and project coordinator in various forestry institutes. He has published many research papers (30), articles, books (2), and book chapters (10) in various national and international reputed publishers. He is also member of several academic societies of India. He has supervised 41 MSc (Farm Forestry) students and involved in teaching (postgraduate) and research.

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Agriculture, Forestry and Environmental Sustainability: A Way Forward

Manoj Kumar Jhariya, Arnab Banerjee,
Ram Swaroop Meena, and Dhiraj Kumar Yadav

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Abstract

Sustainability is a big issue in the modern context, with the focus to sustainable development for the earth will be clean and green. The issues of the environmental damage, forest depletion and food security are all coming under the umbrella of sustainability. Approaches for the sustainable development are a need of time for proper environmental management, boosting up the agricultural productivity, and conservation of the forests with least harm to environment. Proper manage-

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ment of forests resources and eco-friendly agricultural practices would help to maintain the ecosystem services and ecological resilience leading to environmental sustainability. The natural balance of sustainability through effective management of agriculture and forestry sector would help to maintain the ecological systems of the world. As per the Food and Agricultural Organization (FAO), globally 815 million people is suffering from proper supply of food with 155 million children have age group below 5 years without adequate food. As per the reports of the State of Food Security and Nutrition (SFSN) in the world, the global food production needs to be increased up to 50% depending upon population strength and changing dietary pattern. Globally around 3.3 million hectares of forests area were reduced between 5 years from 2010 to 2015. It was found that within a time span of 130 years, the warming of earth's surface has taken place up to 0.85 °C, and level of sea rise has taken place up to 0.2 m within a span of 10 years. Environmental degradation, food security and deforestation are the three-dimensional challenge towards sustainable development. Considering these issues, pathways towards sustainability are yet to be properly explored. Newer technologies would lead to expansion of agriculture and put pressure on other natural resource base. Under such situation, integrity between activities of human being with ecological system is the key to achieve sustainable development. Minimizing use of non-renewable inputs in the agriculture would help to maintain the agricultural sustainability. Protecting the resource base of forests along with promoting various sustainable forest management (SFM) schemes would help to maintain forest sustainability. Lesser pollution and degradation of the environment with a sustained environmental management approach is the key for environmental sustainability. To achieve such conditions, one should go for productive use of indigenous knowledge along with technological expertise. Community participation in all aspects would act as workforce towards achieving sustainable development. However, challenges are there to develop integrated policies both at the national and international level to achieve sustainability in agriculture, forestry and environment. To overcome such challenges, knowledge both at institutional level and policy level would act as appropriate incentive for development towards sustainable earth. The main objective behind writing this title is to address sustainability issues and approaches of conservation in the fields of agriculture, forestry and environment. The present chapter would act as basic guidelines of sustainability approaches for effective management of natural resource.

Keywords

Agriculture · Climate change · Environment · Forestry · Sustainability

Abbreviations

C	Carbon
CDM	Clean development mechanism
CO_2	Carbon dioxide
FAO	Food and Agricultural Organization
GHGs	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
R&D	Research and development
SFM	Sustainable forest management
SFSN	State of Food Security and Nutrition

1 Introduction

Sustainable development is a major issue which incorporates various approaches that address the problem and simultaneous planning towards their solutions (Koutsouris 2008; Cerf et al. 2011). Sustainable development is a theme which embraces the society, economy and environment (Reed et al. 2006). This is an important aspect to addressing survivality of human civilization.

The term sustainability aims towards conserving natural resources without their further depletion. Traditional knowledge and wisdom practiced throughout the world is working towards achieving sustainability of the earth's ecosystem (Parotta et al. 2006). It would bring benefits for the human civilization continuously generation after generation (Reboratti 1999). Sustainable development refers to a developmental process which considers economic, social and environmental dimension (Strange and Bayley 2008; Ashoka et al. 2017).

In this context it has now become very much essential to consider agriculture, forestry and environment as the key issues of sustainable development. Such thinking was also addressed in various international levels such as in the Rio + 20 summits, 2020 and 2030 agenda. The world is going through such crisis that human existence has become questionable. Therefore, eco-resilient approaches in various sector need to be formulated. It was also highlighted in the Rio summit, 1992. As per this summit, major changes in the field of agriculture and environment should be considered for developing policies and strategies (Farrelly 2013).

Agriculture is the major economic process for overall prosperity of human civilization. This has created the problem of gap between demand and supply. With gradual growth of science and technology, the human population is growing at an unprecedented rate. Globally the world food production lies between 2 and 4% during the last 50 years along with increase in cultivable land up to 1% per year. This indicates the improved efficiency of global food production. It was found that eight crop species (barley, beans, groundnut, maize, potatoes, rice, sorghum and wheat) and five animal species (cattle, sheep, goats, pigs and chickens) constitute 53% and 31% protein diet of world human population. Three crop species (wheat, rice and maize) act as major staple food crop for the entire world which fulfils 48% of mean daily calories requirement on global basis (FAO 2016).

As a consequence, one has to go for more production and more output in relatively short period of time. Modernization of agricultural technology has put the entire environment under stress. It is also throwing challenge to the sustainability of the entire environment. Environmental sustainability is such a concept which requires regular monitoring of environmental issues related with developmental process. This is a big issue as adequate data at the base level is a scarce resource at local and national level. In most of the countries, government is in a misnomer position in terms of policy formulation and implementation which would bring benefit for mankind considering environmental sustainability in terms of forest conservation, lesser pollution and enriched biodiversity status. The policy issue does not properly address the issue of livelihood generation and socioeconomic upliftment leading to social sustainability. It has been observed that environmental impact has long-term consequences over future generation. Mega global change events such as changing climate, species extinction, biodiversity loss and alteration of nutrient cycling have severe consequences in the sectors of agriculture, forestry and environment (Rockstrom et al. 2009). Such major problems also give rise to secondary issues in terms of ozone layer depletion, coral bleaching and ocean acidification. This is very unfortunate that at the present era of science and technology, we still do not know the threshold boundary of sustainability and the harmful impacts over human civilization.

Due to overall degradation of the environment, biodiversity loss is taking place at an unprecedented rate. Species extinction has now become a common incidence throughout the world (Rockstrom et al. 2009; Meena et al. 2017; Raj et al. 2018a). The impact would be severe through massive alterations in global ecosystem. The World Bank (2010) suggests that 15 out of the 24 ecosystem services are under the threat of severe degradation due to unsustainable use. As per the reports of IPCC (2014) within a span of 1 year (2010–2011), temperature has increased up to 3%, and this increasing trend continues up to 1–2% within 2011–2012. This is a very alarming situation causing increase in average global temperature (IPCC 2014). FAO estimate (2011) mentioned that up to one third of food items globally were lost or degraded from production to its ultimate destination site. Associated with this is the production of GHGs emission creating the problem of global warming.

The problem of ecosystem service loss would further be aggravated through intense agricultural operation, loss of forests, unprecedented growth of human population and ever-increasing environmental pollution. The worst sufferer would be people under poor economy (CBD 2010). For instance, dieback of Amazon forests through deforestation activity would be the major consequence of forest fire and climatic abnormalities in terms of drought. Gradual building up of nutrients in freshwater ecosystem may convert it into eutrophic condition harbouring algal blooms. Coral bleaching due to ocean acidification increase in sea temperature and other anthropogenic influence may raise the question of malfunctioning of ecosystem and crisis of food. Forest is a key factor for biodiversity conservation, but activity related to forests conservation is yet to meet the target as set by the UNEP

(2010). Climate change would significantly impact the biodiversity in upcoming century. Rising temperatures would influence species negatively by reducing their ecological amplitude. For example, the UNDP (2008) reported gradual rise of surface temperature of 3 °C; up to 30% of terrestrial species would be under the verge of extinction. Average estimates show one tenth of species would become extinct with only 1 °C rise of temperature (World Bank 2010). Changing climate may lead to more pest outbreak, alteration in precipitation pattern and competition for food and habitat (Raj et al. 2018b).

The present book addresses three most important interactive issues which fare the need of the twenty-first century. Rapid growth of science and technology has pushed human civilization to an industrialized and urbanized setup which is mostly technology oriented. Now this has created the problem in the field of agriculture, forestry and environment. For sustenance of life on earth, we need to take care about these issues, and therefore the present book will provide an insight regarding current scenario, R&D (research and development) and way forward towards sustainability. It would have a broad readership at the international arena where there will exchange of knowledge and thinking between scientists, research scholar, teachers and overall academicians. This would be a good platform for people thinking globally, related to sustainability issues of agriculture, forestry and environment. The present chapter would act as a baseline database for the entire book where going through this chapter by the readers would provide them a concise insight about the theme of various chapters present in the book. It would also help the academicians as well as new aspirants in the field of agriculture, forestry and environment to fulfil their inquisitiveness about sustainability and ways to achieve sustainable development.

2 Agriculture, Food and Environmental Security

From food security point of view, two major challenges include higher level of hunger and lack of nutrition which approximates more than 850 million people up to 2012 (FAO 2012a). Poverty alleviation is taking place at a very slow pace, and unsustainable attitude of human being supersedes carrying capacity of the earth. Some major events such as loss of biodiversity, overuse of nitrogen, phosphorous fertilizer, soil degradation and acidification of the ocean are becoming an alarming threat. This has further aggravated the problems of freshwater crisis, degradation of land, loss of forests, less agricultural productivity and lesser livelihood generation. The major problem is that lack of adequate policies to address such issues. Human population growth is taking an alarming rate from 7 billion to 9 billion which is putting pressure on agriculture and natural resources (Alexandratos and Bruinsma 2012; Verma et al. 2015). The situation is very complicated as one needs to design policies to boost up the agricultural production to feed the ever-increasing human population as the situation has now become so worse that optimum food and quality environment is under question for the sustenance of human civilization (FAO 2012b).

Diverse agricultural activities provide diverse economic output through crop production, aquaculture, agroforestry, farm forestry and other allied SFM (sustainable forest management) practices which promote livelihood generation as well as works for poverty alleviation (Jhariya et al. 2015; Singh and Jhariya 2016; Painkra et al. 2016). Therefore, agriculture sector has a huge potential towards addressing the issue of poverty alleviation in comparison to nonagricultural sector. This is very much effective for countries having poor economy system (FAO 2012a). As agriculture has multifaceted role to play, therefore it addresses solution for diverse challenges and issues of environment. In order to make more fruitful output, one needs to move from agriculture to sustainable agriculture practice for overall development of human civilization.

Green revolution is such a concept which involves improved seed and planting materials, improved technology and improved agricultural inputs in order to boost up the productivity of staple food crops in various countries which would strengthen the agricultural sector. This is applicable for the countries of third world nations or agriculture-dependent economy. The positive impact of such process has helped preservation of soil resource as well as forests areas which would otherwise be overexploited through promotion of agriculture (Stevenson et al. 2011). This leads to agricultural growth for small-hold farming community with increase in rural economy and decline in food prices.

Under the present system of modern agriculture, non-judicious application of fertilizer and pesticides and cultivating single cropping degrade the environment. Degradation has taken place in the form of water loss, water pollution, loss of agricultural biodiversity and soil and land pollution. As a consequence of this green revolution in the format of agricultural intensification, this acts as boon and a bane. Food security is the biggest challenge for both developed and developing nations of the world (Fan and Brzeska 2016).

This problem is further aggravated as rising human population has put pressure upon agricultural productivity sector (Grote 2014). As per UN (2015) estimates, we would reach to a production of about 8.5 billion up to 2030, and it will further increase up to 9.7 billion till 2050. Simultaneously, availability of land is also a biggest challenge due to rapid urbanization rate, and more production in a short span of time has created the problem of land pollution (Montpellier Panel 2013). During the last half century, global food production has increased tremendously due to rising demand of average per capita food. Lesser external inputs have led to decline in productivity from world agriculture perspective in some areas such as Africa. The condition is perplexed in case of Africa due to low agricultural productivity and high population growth which have made them from food exporter to importer. A very interesting fact is that agriculture sector comprises of 80 percent of land area in the form of animal husbandry consuming 70 percent of water (Kabat 2013). As a consequence, agriculture is acting as the drivers of environmental deterioration (UNEP 2010).

The major threat in the agricultural sector is the loss of genetic diversity due to global change in the environmental setup and traditional knowledge related to agriculture (MEA 2005). It has been observed that due to intense agriculture activity, there is gradual increment at the level of GHGs. The major consequences of such activities have promoted global climate change leading to rise in temperature and other extreme climatic events. The negative impact includes lowering of agricultural productivity to a considerable extent.

By considering the problems and issues in the agriculture and the environmental sectors along with growing demand for fuel, fodder and wood, one needs to move towards sustainable approach for environmental management. In terms of sustainability, it is essential to address climate adaptation and mitigation, GHGs emission reduction and prevention from natural hazards and maintain soil resources (Pretty 2008; Yadav et al. 2017b; Jhariya et al. 2018a, 2018b). On the energy sector, one needs to go for energy efficiency, use of renewable energy resources, optimum production in the agricultural sector and low wastage.

Sustainable agriculture approach is an ecosystem-oriented approach which involves the use of biological resources to boost up the production in order to avoid risks from pests and diseases. Such approaches also take due consideration about natural resource base and its conservation. Therefore, it is an urgent need to develop programmes aiming towards R&D in agriculture with eco-friendly technologies. Maintaining the germplasm would be a sustainable approach to mitigate and adapt climate change and subsequently agricultural biodiversity (Vignola et al. 2015; Dadhich et al. 2015). Economic incentives should be widely adopted for the farming community for moving towards sustainable agricultural approach from unsustainable one. This requires adequate financial support as well as detailed indigenous knowledge about the farming practices. Some of the sustainable agricultural approach involves worldwide adoption of crop rotation practices, minimum tillage or zero tillage activity, biological control of pests, integrated nutrient and pest management, integrated farming and husbandry practices, drip irrigation, etc.

3 Challenges for Agriculture Sustainability

Agriculture happens to be the backbone of underdeveloped nation for their economic output. Agriculture is associated with major issues such as food crisis and security. Above all the agricultural productivity and quality is degrading day by day along with rising human population. This problem is further complicated by the event of climate change. Going for more production people are cultivating hybrid varieties causing huge loss of traditional crop varieties along with gene pool (MEA 2005). This is a big issue as it would promote degradation in the quality of food. Food quality degradation would lead to malnutrition and other health disorders for human beings. Another big problem is the agricultural pollution in the form of uses of synthetic agrochemicals for crop production and protection. This therefore indicates multidimensional problems associated with the agricultural sector (FAO 2016).

The problem of environmental degradation, pollutions and depletion of soil quality in the form of faulty land-use practices has caused a dramatic change in the scenario of Indian agriculture. There is a total change in land-use practices in the agricultural sector which is a major challenge towards moving agricultural sustainability. As per the reports of agricultural ministries (Table 1), it was observed that

Table 1 Land-use pattern in India

Particulars		Years (area in thousand hectare)			
		2000–2001	2004–2005	2008–2009	2012–2013
Forests		69843.16	69960.01	69978.25	70007.32
Not available for cultivation	Area under nonagricultural uses	23751.84	24760.72	26210.91	26453.97
	Barren and unculturable land	17482.67	17468.24	16581.11	17283.63
	Total	41234.51	42228.96	43062.02	43737.60
Other uncultivated land excluding fallow land	Permanent pastures & other grazing lands	10661.60	10452.12	10344.33	10240.25
	Land under miscellaneous tree crops and groves (not included in net area sown)	3444.77	3361.75	3343.43	3157.24
	Culturable wasteland	13631.05	13271.73	12734.80	12578.20
	Total	27237.42	27085.60	26422.56	25975.69
Fallow land	Fallow lands other than current fallows	10266.93	10878.11	10289.52	11001.35
	Current fallows	14777.06	14972.22	14192.21	15281.66
	Total	25043.99	25670.33	24481.73	26283.01
Net area sown		141335.56	140642.06	141899.08	139932.01
Total cropped area		185340.38	191103.06	195327.91	194398.98
Area sown more than once		44004.82	50461.01	53428.82	54466.97
Agricultural land/cultivable land/culturable land/arable land		183455.37	182945.87	182459.04	181950.46
Cultivated land		156112.62	155434.28	156091.29	155213.67
Cropping intensity		131.13	135.88	137.65	138.92

Sources: Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare; Tea Board, Ministry of Commerce & Industry; Coffee Board, Ministry of Commerce & Industry, Rubber Board, Ministry of Commerce & Industry within 15 years span, the total forest cover has shown an increasing trend throughout the years. Further it was observed that the area under unculturable land also reflected a rapid increase from 2010 onwards. It is very interesting to note that net sown area reflects a flip-flop pattern over the years. Due to increasing demand of human population, the total cropped area and cropping intensity have shown a continuous increase throughout the year. If the area under cultivation along with production is considered, then mixed type of results was obtained. However, every sector of agricultural crops reflected an increasing trend over the years. But, the area under cultivation of each crop sometimes increased and sometimes decreased. Higher production rate might be attributed towards improvement in the technology, more scientific inputs and management and overall adaptability of local stakeholders (Table 2).

Under these circumstances, concepts such as integrated nutrient, pest and water management and organic farming are providing some solutions in the hands of human civilization but yet to be satisfactory in results. Frequent field trials are being organized in the research station to address the sustainability, but lab to land programme is not becoming successful at broader scale. Therefore, more emphasis should be given to lab to land programme and would be incorporated in the nation's action plan to achieve sustainable development.

4 Forestry

Forest is a crucial ecosystem for sustenance of life on Earth's surface. Global coverage of forest lands happens to be 4 billion hectare covering 30% of total available land. From the reports of FAO and Forestry Statistics, it was evident that the total world forest cover appears to be 30.64% up to 2015. The major contribution in the forest cover was done by South America, Europe and North and Central America. It clearly reflects that the forest under tropics is under severe threat. Globally it was observed the total forest area reflected a declining pattern from 1990 to 2015. In Asian subcontinent, contrasting results were obtained between forest cover in million hectares and percentage contribution. In terms of area, there is a rapid increase in forest cover from 2010 onwards, but share of forest cover from world perspective Asia represents minimum (19.02%) contribution (Table 3).

Forest performs the dual function of production of various resources along with maintaining livelihood security. As per global estimates, one fourth of human population is dependent upon forests for maintaining livelihood. Forests also harbour rich heritage of biodiversity along with combating climate change (Jhariya and Raj 2014; Raj et al. 2018a). The problem starts from the point where human's consumeric lifestyle puts significant pressure on this valuable resource. Policy formulation is required towards SFM to arrest deforestation and promote plantation to increase the forest cover.

Forests perform various important services in the form of protecting soil and water ecosystems, nurturing biodiversity (75% terrestrial), forest produce serving to socio-economic development throughout the world (FAO 2014). Global forest

Table 2 Average yield (quintals per hectare) and cultivated area ('000 hectare) of agricultural crops in India

		Year							
		2001–2002		2005–2006		2009–2010		2014–2015	
Particulars	Crops	Area	Production	Area	Production	Area	Production	Area	Production
Food grains (cereals)	Rice (*Oryza sativa*)	44904.00	20.79	43659.80	21.02	41918.40	21.30	43855.34	23.90
	Wheat (*Triticum aestivum*)	26344.70	27.62	26483.60	26.19	28457.00	28.39	30969.07	28.72
	Jowar (*Sorghum bicolor*)	9795.00	7.71	8667.30	8.80	7786.60	8.60	5298.79	9.53
	Bajra (*Pennisetum glaucum*)	9529.00	8.69	9581.20	8.02	8903.60	7.31	7117.58	12.72
	Maize (*Zea mays*)	6581.50	20.00	7588.30	19.38	8262.00	20.24	9257.83	25.57
	Ragi (*Eleusine coracana*)	1647.00	14.42	1533.90	15.34	1268.10	14.89	1200.66	16.62
	Small millets	1310.50	4.40	1064.30	4.43	831.30	4.60	584.64	6.41
	Barley (*Hordeum vulgare*)	659.50	21.60	629.90	19.38	623.80	21.72	689.13	23.25
	Total cereals	100771.0	19.80	99208.0	19.68	98051.0	20.75	98973.05	23.79
Food grains (pulses)	Tur/arhar (*Cajanus cajan*)	3327.70	6.79	3580.70	7.65	3466.00	7.11	3707.81	7.50
	Gram (*Cicer arietinum*)	6416.20	8.53	6926.40	8.08	8168.60	9.15	8191.40	8.75
	Other pulses	12264.50	4.59	11884.20	4.25	11647.00	4.10	11198.77	6.47
	Total pulses	22008.40	6.07	22391.30	5.98	23281.70	6.30	23097.98	7.44
Total food grains		122779.6	17.34	121599.3	17.15	121334.0	17.98	122071.03	20.70
Oilseeds	Groundnuts (*Arachis hypogaea*)	6238.10	11.27	6736.00	11.87	5478.10	9.91	4684.58	14.00
	Sesame (*Sesamum indicum*)	1671.00	4.18	1723.20	3.72	1941.80	3.03	1778.48	4.56
	Rapeseed (*Brassica napus*) and mustard (*Brassica nigra*)	5073.00	10.02	7276.50	11.17	5587.90	11.83	5791.45	10.89
	Linseed (*Linum usitatissimum*)	535.80	3.90	436.80	3.95	341.60	4.49	283.54	5.39
	Castor seed (*Ricinus communis*)	716.70	9.11	864.20	11.46	735.40	13.73	1105.43	15.68
	Total oilseeds	22636.40	9.13	27862.80	10.04	25958.80	9.59	25726.38	10.37

Other crops	Cotton (*Gossypium* spp.)	9132.00	1.86	8677.10	3.62	10132.20	4.03	13083.00	4.61
	Jute (*Corchorus* spp.)	873.10	21.82	759.80	23.62	811.20	24.92	749.12	26.27
	Mesta (*Hibiscus cannabinus*)	174.10	62.84	137.90	11.36	94.30	11.21	59.17	15.67
	Tea (*Camellia sinensis*)	509.81	16.75	555.61	17.08	579.00	17.10	563.98 (2013–2014)	21.42 (2013–2014)
	Coffee (*Coffea* spp.)	347.00	9.40	380.00	8.00	400.00	8.20	423.00	7.73
	Rubber (*Ficus elastica*)	401.00	15.74	447.00	17.96	468.00	17.75	518.00 (2013–2014)	14.94 (2013–2014)
	Banana (*Musa paradisiaca*) (MT/ha)	488.80	26.92	423.60	28.58	770.00	34.36	845.13	37.04 (2013–2014)
	Sugarcane (*Saccharum* spp.)	4411.60	673.70	4201.70	690.22	4175.40	700.20	5143.64	698.59
	Tobacco (*Nicotiana tabacum*)	348.50	15.65	372.80	14.81	441.00	15.60	431 (2013–2014)	15.40 (2012–2013)
	Potatoes (*Solanum tuberosum*) (MT/ha)	1207.90	19.81	1401.40	17.06	1835.00	19.90	2068.95	201.06 (2013–2014)
	Black pepper (*Piper nigrum*)	219.38	2.84	260.22	3.57	199.00	2.60	123.62	4.11 (2013–2014)
	Chillies (*Capsicum* spp.)	880.00	12.15	654.00	15.51	810.00	15.68	743.64	19.26 (2013–2014)
	Ginger (*Zingiber officinale*)	91.30	35.28	110.60	35.37	142.00	35.83	137.51	49.39 (2013–2014)
	Coconut (*Cocos nucifera*)	1932.30	67.09	1946.80	76.08	1895.20	57.10	1975.82	69.66 (2013–2014)
	Turmeric (*Curcuma* spp.)	167.10	33.68	172.00	49.52	188.00	43.82	189.14	51.14 (2013–2014)

Sources: Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare; Tea Board, Ministry of Commerce & Industry; Coffee Board, Ministry of Commerce & Industry, Rubber Board, Ministry of Commerce & Industry

Table 3 Forest area of the worlds by continents (FAO 2010, 2015; Forestry Statistics 2017)

Nations	Total land area (million hectares)	Forest areas (million hectares) in different years					Forest (%) to total geographical area
		1990	2000	2005	2010	2015	2015
Asia	3118.0	576.00	570.00	571.60	592.50	593.00	19.02
Africa	2987.00	749.00	709.00	635.40	674.40	624.00	20.89
Europe	2214.00	989.00	998.00	1001.30	1005.00	1015.00	45.84
North and Central America	2134.00	708.00	705.00	705.80	705.40	751.00	35.19
South America	1747.00	946.00	904.00	831.50	864.30	842.00	48.20
Oceania	850.0	199.00	198.00	206.20	191.40	174.00	20.47
World	13050.00	4167.00	4084.00	3951.80	4033.00	3999.00	30.64

resource assessment (2015) mentioned that within a 25 years span, the forest cover has reduced up to 129 million hectares (FAO 2015).

Within a span of 10 years (2000–2010), tropical deforestation is taking place up to seven million hectare/year in comparison to agricultural land area, which has increased up to six million hectare/year. Commercial agriculture practice accounted for 40% of tropical and sub-tropical deforestation, 33% loss is accounted by subsistence agriculture, 10% due to infrastructure development, 10% for urbanization and 7% for mining (FAO 2016). Further loss of forest due to natural expansion and planted forest establishment ranged between 2.2 and 3.1 million hectare/year.

The United Nations Strategic Plan for Forests (2017–2030) vision of checking deforestation would promote prevention of degradation of environment (UN 2017). The 2030 agenda of UN convention also works towards this same aim to combat desertification with joint collaboration of forest department and public administration. From forestry perspective, 2030 agenda includes various issues such as forest management, ecological restoration, checking of biodiversity loss, etc. The theme was given prior importance by UN general assembly by declaring 21st March as the International Day of Forest. The main theme behind this approach is to simply increase the forests cover globally. Simultaneously it would work for well-being of forest dwellers. In this context the UNCCD, UNFCCC and CBD should work hand in hand to build up a network system for protecting forests worldwide.

Worldwide Indian forests contribute significantly towards GHGs emission reduction by cutting down 12% of emission reduction across the country. It also provides habitat of threatened biota. Recently as per Bonn Convention, a biggest challenge has come into our forefront for targeting ecological restoration of forests up to 13 million hectare area till 2020. It also addresses such approaches through green India mission. Green India mission is aiming towards further 2.5–3.0 billion tonnes more additional C sequestration from Indian perspective.

Forests are major issue in terms of resource, ecological sustainability, biodiversity and changing climate. Major challenges in forestry include activity related to deforestation as well as over harvesting of forest resource. Natural calamities pose significant threat for surveillance and ecological integrity of the ecosystem. Forest has a big role to play in C sequestration as well as mitigating climate (Jhariya 2017; Yadav et al. 2017a). Therefore, sustainability in forestry requires an integrated approach that addresses all-round development of the forest sector without damaging the environment.

SFM is a step towards achieving sustainability in the forestry sector. SFM involves a systematic management procedure for optimum utilization of forest resource on one hand and checking deforestation rate on the other. Considering sustainability the socioeconomic upliftment of forests dwellers was also given due consideration through livelihood generation in terms of non-wood forest products (Chandel et al. 2017). Depending upon the site condition, SFM has reached considerable amount of support throughout the world (McDonald and Lane 2004). Even at Europe, SFM is considered as a technique for the society as well as a way forward towards sustainable development (Angelstam et al. 2004). SFM is an integrated approach that keeps in mind about maintaining the productivity level, conservation of biodiversity, increase in regeneration potential for now and future generation in terms of social, economic and environmental standpoint (Forest Europe 2011).

Siry et al. (2005) mentioned that under tropical condition, SFM is initiated by the International Tropical Timber Organization. Globally under the banner of the twenty-first-century agenda as well as United Nation Conference on Environment and Development SFM, statement of principles for forests were adopted by nearly 180 government agencies (Barrutia et al. 2007; Varma et al. 2017).

In the pathway of forest sustainability, model forests are a stepping stone initiated in Canada aiming towards addressing SFM and sustainable development (IMFN 2008). The concept is based upon six major principles (IMFN 2008) aiming towards sustainability (Fig. 1). The major flexibility of this approach includes initial facilitation between stakeholders for smooth execution of the project and later on the various stakeholders that would play the key role to move the project forward (Axelsson and Angelstam 2006). However the major challenge for model forests includes meeting up the disparity between the various stakeholders and their opinions involved in the project. The applicability of model forests has promoted the concept in the 24 countries across the world and gradual development of international model forests network consisting of 60 members. Latin America leads from the front in implementing the model forests (Sinclair and Lobe 2005).

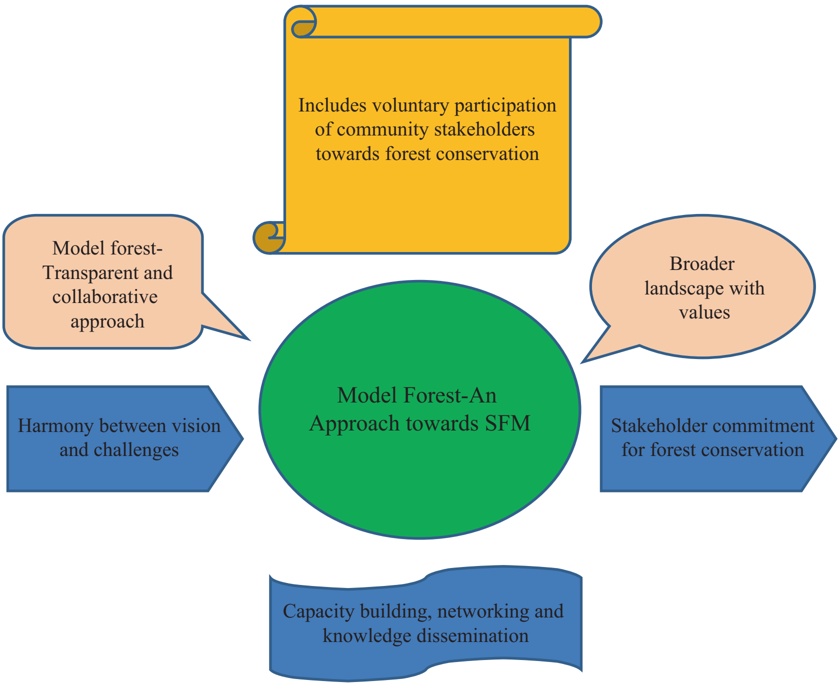

Fig. 1 Approaches of model forests. (IMFN 2008)

Data presented in Table 4 reflects a comparative account of forest products generated in Asia and the rest of the world. It was observed that fuelwood production, industrial wood production and total wood production showed an increment both in Asia and the rest of the world reflecting the increasing demand of human population. Further, if percentage share of fuelwood is considered, it is evident that the percentage share showed a declining pattern in relation to other wood production. This is a very alarming situation as it reflects more deforestation and depletion of natural resource in the form of over-exploitation of fuelwood. The database reflects that Asia has a contribution of industrial wood of about 17.26% in comparison to the rest of the world. From the total wood production perspective, Asia contributes 30.09% in comparison to the rest of the world.

5 Challenges Towards Sustainability of Forests

In modern context, forests produce a severe challenge for its sustainable management. With growing population and higher resource dependency, forest depletion is taking place at a steady pace. Expansion of agriculture area to feed growing population at the cost of deforestation is the most significant factor towards forest depletion. Further this problem is aggravated by climate change producing natural calamities and climatic extremes leading to total loss of ecological value of forests (Jhariya and Yadav 2017). Alternate land-use practices such as conversion of forests land for non-forest purposes in the form of industrialization, urbanization and even within the system unsustainable approaches such as shifting cultivation are posing severe threat on these valuable resources. Moreover, throughout the history, forests have been observed as a ready resource to mankind in terms of medicine, non-timber forest products, timber wood, etc. Natural factors such as forest fire also pose significant challenge in front of sustainability of forests (Kittur et al. 2014a, 2014b; Jhariya et al. 2012, 2014). Therefore, an urgent need of strategy formulation is required for effective management, protection and conservation of ecosystem. In this direction, SFM is a significant step.

SFM, although a key step towards achieving sustainability in forestry sector, has got some major issues which hamper its efficient executions. The key sectors of SFM creating problem include the framework for policymaking, stringency of governments, market and marketing management, exact valuation of forest resources, capacity building for local community stakeholders and sufficient funds for implementing the schemes under SFM. Development of technological growth, improved innovation and sectoral planning would govern the success of future SFM policies. Collaboration between forests dwellers, private sector and government agencies is also very much important for linking sustainability in the field of forestry. This would also bring into consideration of various constraints and scope.

The World Bank (2004) in its forests strategies along with operation policy on forests aims towards working for the issue of sustainability in terms of poverty eradication through SFM maintaining ecological integrity. Strategies include exploration of forests potential for poverty alleviation, integrating forestry with sustainable development and concerning about ecological services of forests.

Table 4 Comparative account of Asia's wood production (million cubic meters) scenario in the world

Year	World				Asia			
	Fuelwood	Industrial wood	Total wood production	% share of fuelwood in total	Fuelwood	Industrial wood	Total wood production	% share of fuelwood in total
1961	1498.58	1017.83	2516.41	59.55	838.69	131.92	970.61	86.41
1971	1550.36	1296.44	2846.80	54.46	866.30	176.54	1042.83	83.07
1981	1703.29	1411.86	3115.15	54.68	904.53	224.40	1128.93	80.12
1991	1863.07	1558.13	3421.20	54.46	895.61	257.91	1153.52	77.64
2001	1795.67	1540.68	3336.35	53.82	801.26	233.76	1035.02	77.41
2011	1878.20	1557.24	3435.44	54.67	764.78	268.85	1033.63	73.99

Source: FAO (2012)

6 Environment

Our surrounding has become a crisis scenario due to anthropogenic activities in the name of development. Science and technology has sufficiently contributed towards alteration of natural habitat. This has created the need of management from sustainability perspectives. It includes eco-friendly approaches, i.e. environmental protection, management of natural hazards in the form of preventing desertification, drought protection, proper utilization of natural resource, ecological restoration and maintaining overall integrity (Jhariya et al. 2018a). To achieve sustainable development, one should take care about these aspects. In this regard, environment is a very important issue for prosperity of human beings. Moreover it is an integrated concept which addresses various issues of environment. Sustainable environment is based upon eco-friendly lifestyle which would provide good health, pure water and proper nutrition to the entire human civilization. In order to achieve this community participation, proper networking and framework under the banner of proper decision-making would help to achieve the sustainability. It is a very well-known fact that all the resources that we get are provided by nature, but over-exploitation and abuse have created the problem of exceeding the carrying capacity of the habitat, so environmental degradation is the fate.

One common consequence of environmental degradation includes infant mortality simply due to poverty and malnutrition along with improper health and hygiene. Disease infestation seems to have become very easy in this unsustainable way of living in the name of development. Reports revealed throughout the globe approximately 3.5 billion people are devoid of good quality food and pure water. It has been observed that international conferences such as the Montreal Protocol and Vienna Convention have also moved towards addressing policies that come under CDM to achieve sustainable development (UNEP 2015). It has been found that adapting eco-friendly technology can reduce global warming up to 0.5 °C thus helping >two million people to avoid hazards of climatic extremes.

Sustainability in terms of the environment is the biggest challenge as development process is retrospective for environment. From a global perspective, it has been found that through MEA (Millennium Ecosystem Assessment), entire ecosystems of the world are under severe threat of degradation. Such assessment procedure also highlights that if we do not take any initiative towards environmental sustainability, the entire ecosystem of the world would be degraded, and simultaneously human civilization would become under a big question of survivability. Therefore, we need to inculcate the concept of environmental sustainability into our planning process in order to achieve millennium development goals. It addresses major sustainability issue such as poverty eradications and food security. Developing countries can adopt such principles aiming towards sustainability as their development goals to fulfil millennium development goals. Moving towards green economy and green jobs is often not integrated in the planning process which may act as a major pathway to achieve environmental sustainability. These are such types of concept where development takes place, fulfilling the needs of human beings without damaging the earth's ecosystem (UNEP 2010).

Environment is a wonder word which is approached by different thinkers in different ways. It considers variety of issues such as biodiversity conservation, protection, combating deforestation, ecological restoration of tropical rainforest, etc. With gradual growth in science and technology, the environment is moving towards unsustainable direction. Therefore, an urgent need of adopting procedures would facilitate eco-friendly and green development. Environment is such a context which not only deals with present generation but also future generation. Throughout the world, the 1992 Earth Summit is the gateway of understanding environmental problems in the context of social-economic and technological arena. The last two decades were the stepping stone for understanding environmental changes and developing policies and ways to combat them. Throughout the analytical period, it was found that lifestyle and living conditions are the two key factors that are posing major impacts on the environment (UNEP 2010).

In environment, all the components are interrelated with each other in a complex way. Therefore, impact due to unsustainable approach does not lie on in a single layer, but it propagates further. For example, the single event of climate change is changing the climatic pattern, altering hydrological cycle, causing biodiversity loss, reducing productivity and overall causing environmental degradation in the form of natural calamities.

Environmental perturbation globally throws challenge for the entire world throughout last two decades. As time passes away, the challenges are increasing day by day. For example, emission from energy and transport sector would increase the concentration of GHGs emissions in a progressive manner up to 2030. It has also being projected that there would be an increase in 10% of land area as agricultural land which would contribute towards doubling the rate of soil erosion. Resource depletion is another major consequence under the pressure of increase productivity. However, attempts have been made to reduce the GHGs emission in relation to per unit of gross domestic products and go for better and more conservation of reserve areas for effective governance. The pressure of GHGs emission and biodiversity loss from ocean perspectives has become so severe that it would be a major problem for upcoming 20 years. Developmental policies with the aim of poverty alleviation should take due consideration in terms of environment and natural resource issues to avoid possible negative consequences on future generations.

In Asian subcontinents, the air pollution is becoming an alarming threat as the level of SO_2 emission increases from 0 to up to 60 million tonnes annually. The condition is worst for North and South America as more than 140 million tonnes annual emission have also been reported (Table 5). From PM 2.5 emission perspective across the various sites, most of the areas have crossed the limits of the World Health Organization (WHO) recommended level. The situation is worst in the case of Africa, Asia and Middle East (Table 6). In relation to PM 10, the situation has further worsened for Asia and Africa (Table 7).

Table 5 Annual SO_2 emission in million tonnes across the world

Area	1850	1880	1900	1920	1940	1960	1980	2010
Africa	0	0	0	0	0	Between 0 and 20	Between 0 and 20	Between 0 and 20
Asia	0	0	Between 0 and 20	Between 0 and 20	Between 0 and 20	Between 20 and 40	Between 20 and 40	Between 40 and 60
Europe	Between 0 and 20	Between 0 and 20	Between 0 and 20	Between 0 and 20	Between 20 and 60	Between 60 and 100	Between 100 and 120	Between 60 and 80
North America	Between 0 and 20	Between 0 and 20	Between 0 and 20	Between 20 and 40	Between 40 and 60	Between 60 and 120	Between 0 and 20	Between 100 and 140
South America	Between 0 and 20	Between 0 and 20	Between 0 and 20	Between 20 and 40	Between 40 and 60	Between 60 and 100	>140	Between 100 and 120

Source: Klimont et al. (2013), Clio Infra (2014)

Table 6 Annual mean PM 2.5 emission in μg/m^3 across the world

Area	PM 2.5 (μg/m^3)	WHO recommended level (μg/m^3)
Africa	100–150	10
Asia	>150	10
Europe	>50	10
North and Central America	>50	10
South America	>50	10
Middle East	150	10
Oceania	<50	10

Source: WHO (2016)

Table 7 Annual mean PM 10 emission in μg/m^3 across the world

Area	PM 10 (μg/m^3)	WHO recommended level
Africa	>500	20
Asia	>500	20

Source: WHO (2016)

7 Environmental Sustainability and Its Challenges

The changing pattern and change of global environment has raised some serious consequences; it is a well-known fact that agriculture output is posing significant pressure on the resources of natural environment. Therefore, environmental footprint is gradually increasing day by day. Technological intervention has reduced the environmental footprint to a considerable extent, and as a consequence, the opportunities for further reduction have become tougher. For example, emission from agriculture sectors has increased to a considerable extent in the last decade (EPA 2014). Therefore, continuous monitoring along with economy-based market incentives are likely to be designed (Schulte et al. 2013).

As per the Department of Agriculture, Food and the Marine, 2020 food harvest would generate a negativity upon environment which needs to be properly managed (Farrelly 2013). Subsequently the growth of agroindustry would impose a positive influence over environment which needs efficient dealing in reduction of environmental consequence towards sustainability approach. A global initiative in the form of emission reduction is changing in a continuous way. For example, GHGs emission reduction target is easily bypassed by the targets set for 2030 agenda considering the potential role of forestry and other vegetation in sequestering C (Schulte et al. 2014; Buragohain et al. 2017).

Throughout the world, there is an intense competition for achieving sustainability for both developed and developing nations. Worldwide government is taking initiatives to develop green credentials among various countries. Schemes such as agroforestry, social forestry, farm forestry, organic farming and conservation agriculture are being implemented to promote national level C sequestration. As per Schulte et al. (2014), sufficient land area is available to meet the target of food harvest of 2020 as well as environmental targets.

India is moving forward a population explosion as a number of individuals have increased from 117 km^{-2} to more than 380 individuals km^{-2} within six decades. Due to such increase in population load, it was observed that having only 2.5% land area, it supports more than 15% of world's population. Percentage contributions of urban population have increased from 11.4% to 31.16% within a decade (Chopra 2016).

The annual rate of increment have been reported up to 4.7% in terms of gigaton CO_2 emitted. However, this rate has lower down little bit within a time span of 2006–2012 in Indian perspective. India contributes 5.7% CO_2 emission annually in the form of primary energy supply coming mostly from coal combustion. In comparison to China, it was found that per capita emission of CO_2 for India is four times lower. Even emission of UN states happens to be eight times larger than India (BP 2017). GHG emission has increased from 785 million ton CO_2 eq year^{-1} to >3100 million ton CO_2 eq year^{-1} within a span of four decades. There is a shifting paradigm of non-CO_2 GHG emission due to lesser agricultural practices (BP 2017). Comparative assessment between developed and developing nations reveals that the per capita emission of CO_2 is much less in developing nation in comparison to developed nation (Chopra 2016).

From global perspective, it was observed there is rapid change in the environmental scenario across the world. As a consequence of this environmental degradation, deforestation, depletion of natural resource and many other allied unsustainable changes are taking place at a rapid rate. Therefore, to combat such problems, there is an urgent need of framing of policy in the form of GHGs emission reduction, promotion of green technology, conservation of natural resource and go for alternate source for sustainable utilization and maintenance of environment. The issue of environmental sustainability is oriented across this dimension which needs to be carefully addressed. Such problems may be curbed through sustainable approaches such as sustainable forest management, eco-restoration, conservation of agriculture, recycling of natural resources, organic farming, sustainable lifestyle as well as awareness regarding environment and its changing scenario.

8 Green Growth Roadmap in Indian Perspective

The major aim for green growth includes going for economic development keeping in pace with the society and also environmental sustainability. The Ministry of Environment, Forest and Climate Change has considered green development as their prime theme to resolve the issues of poverty. Green growth has been oriented in such a way so that it is environmentally sustainable along with socioeconomic upliftment. Moreover, the theme is central for the Ministry of Environment, Forest and Climate Change and Finance Commission of India. In this approach, the 14th finance commission has already taken initiative to provide incentive to the state having optimum forests cover represented by moderate to dense forest cover. In the energy sector, the target for achieving renewable energy of 175 gigawatt up to 2022 is already being initiated. More increase in the production in energy sector would be channelized to the National Clean Energy Fund. Under the banner of green growth, Government of India has initiated a smart city mission to provide good quality environment for its citizens which would progress the country towards environmental sustainability (GGGI and TERI 2015).

Two frontline committees of centre and state government are incorporating the issue of climate change into national development policy issues which prioritizes the issues of climate mitigation and adaptation. Eight broad themes based on energy resources, agriculture, eco-friendly habitat, traditional and indigenous knowledge and water resource were duly considered under the scheme. Joint collaboration has been undertaken between the national action plan on climate change and state action plan on climate change to consider climatic perturbations in the policies of national and state level.

India is considering policies issue to move forward towards sustainable living and has developed various agendas to achieve sustainable development. First of all we need to go for CDM instead of rapid economy growth, followed by emission reduction up to 35% till 2030 from the base level of 2005. Promote development in the field of energy resource up to 40% of non-fossil origin under the supporting hands of technology transfer and cost-effective financial support from funding agencies at the international level such as the Green Climate Fund. Further to build a C sink of about 3 billion tonnes equivalent to CO_2 sequestration by plantation till 2030.

As per various policy formulations, action plan and agendas at national and international level priority should be given on to various afforestation and reforestation programmes to protect the existing forest cover as well as promote higher production by increasing forest cover. Within a span of 30 years, it was found that forest cover has increased to some extent even after the immense pressure of rising demand of human population as well as resource dependency from rural stakeholders' point of view (Table 8). For climate mitigation and adaptation, area vulnerable towards climate change needs to be specified, and proper action plan needs to be developed. Future R&D needs to be designed through collaborative work both at national and international levels to mitigate climate change and move towards overall sustainability.

Table 8 The statistics of Indian forest cover between three decades time interval

Year	Area in km^2	% forest cover of total geographical area
1987	640,819	19.49
1991	639,364	19.45
1995	638,879	19.43
2001	653,898	19.89
2005	690,171	21.00
2011	692,027	21.05
2013	697,898	21.23
2015	701,673	21.34
2017	708,273	21.54

Source: FSI (1987–2017)

9 Sustainability and Sustainable Development

The sustainable approach orienting towards agriculture, forestry and environment centres on various aims and objectives. It includes boosting up productivity with lesser harm to the environment, addressing food security and hunger, improving food quality, sustainable management of ecosystem and forests, prevention of environmental degradation and desertification, checking of loss of biodiversity, conserving water resources and sustainable use of energy resources in an intricate manner (World Bank 2003; UN 2015). Addressing such issues, different programmes have been launched in different countries such as Foresight Projects of British Government, One World No Hunger by German Government and African Projects on agriculture and technological intervention (World Bank 2008).

Addressing food security for achieving social sustainability, one needs to move from unsustainable agriculture to sustainable agriculture practices. Strategies should be oriented to an eco-friendly dimension to move forward with a three-dimensional mode of sustainability. Policies related to climate change adaptation and innovativeness in technologies for agriculture-based countries for better and more production may minimize the environmental impacts and would help to achieve sustainable human civilization (Tilman et al. 2011; Meena et al. 2016).

Sustainable agriculture intensification and agroecological intensification were attributed as key pathways towards achieving agricultural sustainability. Agroecological intensification comprises of ecological orientation of sustainable agriculture, i.e. going for eco-friendly farming practices such as organic farming, biofertilizer technology, green manuring, etc. On the other hand, sustainable agriculture intensification is based upon natural resources and indigenous technologies that would reduce the environmental degradation (Wezel et al. 2015; Meena and Yadav 2014). Bonn Convention held at Germany (2017) has emphasized of protecting forests in the river fringes which is a very fragile ecosystem. Ecological restoration practices on the riparian habitat have now become a worldwide agenda to promote sustainable development in terms of water conservation, soil conservation, forest conservation and above all biodiversity conservation (Jhariya and Yadav 2019).

From future perspective, one needs to go for sustainable agricultural practices in order to combat the food security problems. As per the recommendation of UN secretary general, during Rio + 20 conference, sustainable developments framework should include the issues of poverty eradication and rural development as a major issue. Subsequently agricultural productivity should be increased considering the food crisis and malnutrition aspects. Interlinkage between technology and development should be aimed towards achieving specific goals considering cross-cutting issue. Provide a common platform of open discussion among various stakeholders regarding food security and crisis. Approaches leading to sustainable development include eco-friendly thinking on one hand and its subsequent execution on the other. It includes conservative approach, minimizing input-output, go for innovations, R&D for development of sustainable technology, etc. (Fig. 2).

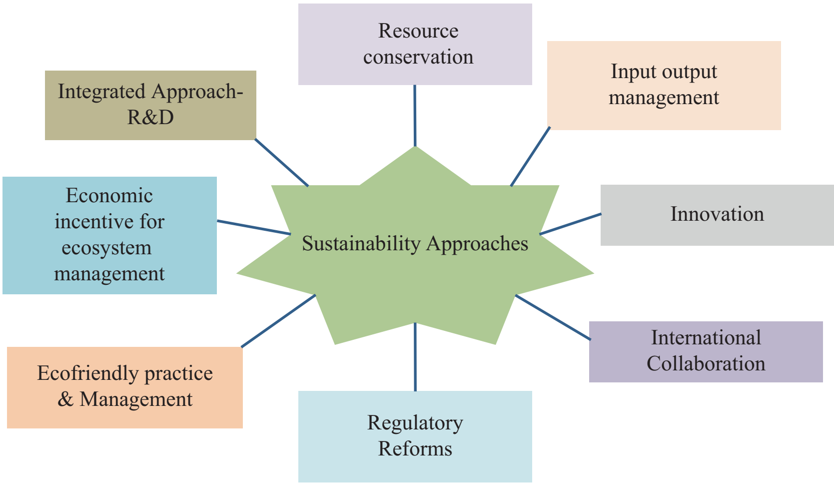

Fig. 2 Approaches towards sustainable development. (FAO 2016; UN 2015; Angelstam et al. 2004; Fraser et al. 2006)

10 Future Prospects of Research and Development Vis-a-vis Sustainable Management

Sustainability is broader concept from environment, forestry and agriculture perspective. Therefore from the future point of view, action plan needs to be designed in a specific orientation (Fig. 3).

Specific agenda need to be screened, and its solutions towards sustainability should be sorted out. For example, with rising demand for food, there is urgent need of boosting up agricultural production, and to combat climate change, reduction in GHGs emission is required, providing safe water for the entire world and good ecological condition for maintaining biodiversity. As per the sustainability aim, problem-oriented policy formulation is an essential requirement. As for the aforesaid problems, greater land area for plantation should be brought under policy matter in order to reduce GHGs emission. For protection of both soil and land, policy should be designed to maximize the ecological health benefits of soil ecosystem. Further good ecological health of land helps to enrich biodiversity. It is a well-known fact that more C sequestration led to lesser ambient CO_2 level, lesser climate change and optimum climate conditions for biodiversity to prosper. In this way specific problem-oriented approach is very much essential for integrating all the dimension of sustainability into a nutshell. This integrated approach would be also helpful for solving multidimensional problems leading to sustainability.

A conceptual framework should be developed in order to address specific issues of sustainability. The framework will work in a holistic pattern addressing the multidimensional problems. Some of the policy issues may be traded across various regions for global benefits such as C sequestration which would develop the C economy across the world through C trading and C credits under clean development

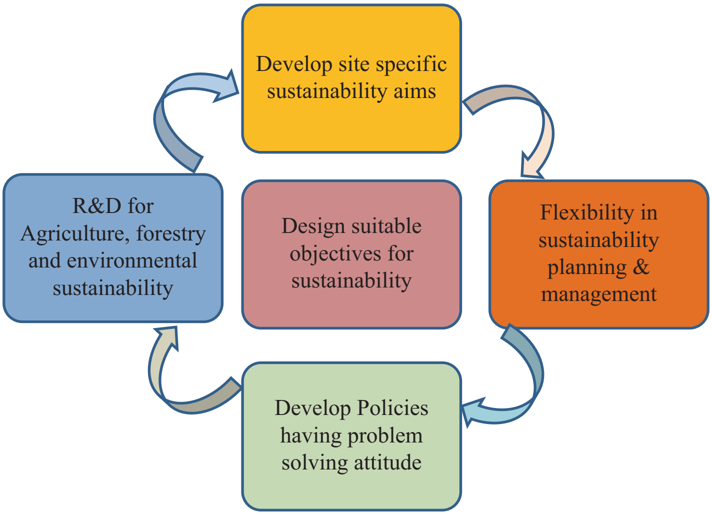

Fig. 3 Way forward towards sustainability. (Fraser et al. 2006; UN 2015; FAO 2016)

mechanism thus helping to mitigate changing climate. Some of the policies cannot be traded across various regions such as water scarcity which should be solved at local level, i.e. think locally, act globally. Therefore, framework helps and needs to be designed towards issue-specific problem-solving approach.

The integration between issues and technical expertise would address various aspects related to equity in benefit sharing, beneficially and technically suitable strategies depending upon societal demand, which is an essential prerequisite to move towards sustainable development. R&D issues, transfer of knowledge and interrelationship between environment, society and economy have a major role to play towards achieving sustainability (Fraser et al. 2006; Datta et al. 2017).

11 Conclusion

Sustainable development in modern context is a big issue which addresses the society, environment, forestry and agriculture. Issue of climate change is jeopardized under these broader themes which makes the situation very challenging. In simple term, by environment we mean the ambience around us, the term forestry implies science of plantation, and agriculture is the production unit. Therefore, every sector is interrelated with each other in an intricate manner, and therefore, sustainability would lead to maintain the harmony between them. Each of us should recognize the indigenous value that lies behind this word for prosperity of human civilization. So considering the future perspective, we are having sustainable approach such as sustainable agriculture, SFM and CDM under environmental management to move towards a sustainable world.

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Mitigating Climate Change Through Bioclimatic Applications and Cultivation Techniques in Agriculture (Andalusia, Spain)

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Abstract

Bioclimatology is applied to agricultural and forestry ordinations, as farmlands and woodlands have a bioclimatic optimum for their development. It is essential to consider the thermo-climate and ombro-climate of the bioclimatic belts in the ordination of the territory to guarantee the maximum yield with minimum environmental costs. These bioclimatic parameters (thermo-climatic and ombro-climatic index, It/Itc and Io) are of particular interest in agriculture as a way of mitigating climate change. The main objective is to establish the climate trends and propose a phyto-bioclimatic model to mitigate sudden climate change in agriculture. The spatial pattern of temperature trends in southern Spain (Andalusia) between 1975 and 2007 was determined by analysing time series data from 48 climate stations distributed homogeneously throughout the study area on a monthly, seasonal and annual basis. The regression slopes were calculated with Sen's test, and the statistical significance of the trends was determined using the Mann-Kendall non-parametric test after pre-whitening the series with autocorrelation. The trends detected on the maps were spatially visualised by applying geo-statistical data interpolation techniques. The study found that positive trends have prevailed over negative trends in the last three decades, with increases of up to 4 °C in spring and summer clearly reflecting the highest percentages of stations with a significant positive trend (92% and 85%, respectively). The trends towards the greatest temperature increase were observed in May and June, with somewhat more moderate increases in April and July. Increases in the range of 0.15–0.4 °C/decade were found at the annual level with 87% of stations significant. The temperature increase reduces flowering and produces losses in agricultural yield as a consequence. It is demonstrated that the vegetation cover acts as a soil water reservoir and retains moisture during the summer months.

Keywords

Bioclimatology · Change · Climatology · Mitigation · Plant association · Trends

Abbreviations

Alt	Altitude
ETP	Potential evapotranspiration
Io	Ombrothermic index
IPCC	Intergovernmental Panel on Climate Change
Is	Summer ombrothermic indices
It/Itc	Thermo-climatic index
P	Precipitation
PAV	Period of vegetative activity
RC	Soil water retention capacity
Tm	Mean temperature

1 Introduction

The fourth report by the Intergovernmental Panel on Climate Change (IPCC 2007) states: “Warming of the climate system is unequivocal”. The third assessment report highlighted an increase in temperature of approximately 0.6 °C [between 0.4 °C and 0.8 °C] (1901–2000) (IPCC 2001), affecting physical and biological systems in different parts of the globe. The fourth report contains clear evidence that climate change and global warming are now incontrovertible facts that affect us all. Global concentrations of carbon dioxide, methane and nitrous oxide in the atmosphere in recent years have increased considerably as a result of human activity since 1750. This linear trend over 100 years (1906–2005) is now calculated at 0.74 °C [between 0.56 °C and 0.92 °C] (IPCC 2007) and not the 0.6 °C cited in the third report. The increase in temperature is distributed over the entire planet but is more pronounced in higher northern latitudes. The IPCC has recently reported different scenarios with temperature oscillations between −1.0 and + 3.5 °C depending on the territories.

Numerous studies at different climatic and regional scales on the Iberian Peninsula have revealed a general increase in temperature throughout history in the whole of the Spanish territory. These include the works of Del Rio et al. (2011), Ileana and Castro-Diez (2010), Brunet et al. (2009) and others such as Sáenz et al. (2001), Salat and Pascual (2006), Del Río et al. (2018) and Martinez et al. (2010) in northern Spain and Esteban-Parra et al. (1997), Castro-Diez et al. (2007) and Ordonez (2008) in the south, specifically in Andalusia.

This accelerated rate of climate change is leading to a wide range of impacts with direct and indirect effects. Several studies have been carried out in Spain such as those by Rodriguez-Fonseca and Rodriguez-Puebla (2010), Brunet et al. (2009) and Moran Tejeda (2011), among others, in addition to similar assessments at the continental (ACACIA project in Europe) and national level (ECCE project in Spain).

Due to its location and complex orography, the Iberian Peninsula has a highly variable climate (Font Tullot 2000) and is particularly vulnerable to climate change. It is subject to the influx of Atlantic depressions on one hand and to the influence of the Mediterranean cyclogenesis on the other; it is also under the influence of high pressure from the Siberian anticyclone and is an area of advection for the subtropical Atlantic winds and for dry winds from North Africa. Over many years, this variability in its climate has been the subject of many different types of studies on a wide range of topics (Capel 1998; Capel 2000; Sigro 2004; Almarza and Luna 2005; Martin-Vide et al. 2006; Beranova and Huth 2007; Dadhich et al. 2015).

According to the IPCC (2007), the Mediterranean area is one of the regions deserving special attention in terms of possible impacts from climate change. Climate change forecasts point to the likelihood of an increase in the frequency of heatwaves, maximum temperatures and a drop in precipitation, all of which may have important consequences on natural ecosystems and on society, health and the agricultural economy. Andalusia will be particularly affected, as climate change exacerbates desertification and erosion processes and leads to a scarcity of water resources due to deforestation, overexploitation of aquifers and a generalised loss of biodiversity in coastal and humid areas and woodlands. The loss of a vast carbon dioxide sink such as forests due to cutting, fire or changes in land use has caused an increase in carbon dioxide concentrations, which further aggravates the situation (IPCC 2007).

Bioclimatology evidently has much to offer in these cases. The indices of Rivas Martínez and Loidi (1999) have established a close correlation between bioclimatic data and plant communities, so each territory can be characterised in these terms. This bioclimatic approach can be applied to a range of crops under a Mediterranean macro-bioclimate. The correlation between these indices and the distribution of olive (*Olea europaea*) cultivation clearly highlight the typically Mediterranean character of olive.

In Andalusia, agriculture plays a key role in the economic sustenance of the population, and most of the region is characterised by a predominance of farmlands. This sector can expect to see major changes, including a declining trend in yields in warmer regions due to heat and water stress. An increase in insect plagues, damage to crops, increased erosion rendering land unproductive due to an increase in heavy rainfall, salinization of irrigation waters, estuaries and freshwater systems due to rising sea levels will all have important social and economic repercussions. It is essential to analyse parameters such as temperature, rainfall and bioclimatic indices in combination with studies of agricultural yields (Cano et al. 1997; Meena et al. 2015) to determine how variations in these parameters will affect the territory and to what extent. This will allow us to create models for short- and medium-term adaptation that can alleviate the situation.

Bioclimatology as a science explores the close relationship between living beings and physical factors (climate) and thus has a strong association with agriculture, as the concepts of bioclimate and bioclimatic belt (thermotype and ombrotype) are essential for planning crops. It should be noted that the aim is to achieve the maximum yield in terms of quantity and quality with the lowest environmental and economic cost as societal demand. The only way to achieve this is to understand bioclimatology as a basic science in agricultural planning. The management of bioindicators and bioclimatic indices must therefore be incorporated into the management of olive cultivation, for which the essential framework is the bioclimatic interpretation of the territory. The treatment against pathogens and the costs incurred by the use and, in some cases, abuse of irrigation in areas of olive cultivation are not the same in different ombrotypes (semiarid, dry, subhumid), as the utilisation of water reserves and the type of crop must be adapted to the thermotype (It/Itc) and ombrotype. Olives are the predominant crop; they are cultivated over a broad area and are of exceptional socio-economic importance.

Biogeographical analyses and soil studies must therefore be conducted in potential sites for olive cultivation. Based on this information, Cano et al. (2003a) propose a model for agricultural management.

Environmental factors → Bioclimatology and biogeography → Vegetation series → Cultivation type

When applied to rainfed crops, this model will ensure a correct territorial ordination. In previous works (Cano et al. 1997), we established a close correlation between kg/hectare yields of olive-growing areas and the values of the ombrothermic index (Io), continentality index (Ic) and thermicity index (It/Itc). This correlation established that the areas of maximum yield for the *Picual* (known as Martena or Loperena, is an Spain olive cultivar) variety are in the upper and upper-dry thermo-mediterranean and lower, upper-dry mesomediterranean bioclimates, and the values of the Io, Ic and It/Itc indices for maximum olive yields for the *Picual* variety are Io = 3.66, Ic = 18.5 and It/Itc = 270/330, coinciding with certain vegetation series. Some years later, we extended these studies to other olive varieties: *Hojiblanca*, *Lechín*, *Morisca*, *Manzanilla*, *Gordal* and *Verdiales* (Cano et al. 2004; Cano-Ortiz 2007; Cano and Cano-Ortiz 2013; Cano-Ortiz et al. 2014). The main objective of this work is to measure climatic and bioclimatic trends in order to establish models and cultivation techniques that serve to mitigate climate change in agriculture.

2 Material and Methods

2.1 Study Area

Our study area is Andalusia, which has an extension of 87,268 km^2 and is located in the south of the Iberian Peninsula. It serves as a bridge between Africa and Europe, and a meeting point between the Atlantic Ocean and the Mediterranean Sea.

Andalusia lies between parallels 36° and 38°44’ N. It is the second largest region in Spain and occupies 17.3% of the Spanish territory and around 2% of the territory of the European Union. In total, it has 910 km of Atlantic and Mediterranean coastline and is divided into the eight provinces which are classified as western Andalusia, Seville, Huelva, Cadiz and Malaga, and eastern Andalusia, Jaen, Cordoba, Granada and Almería (Fig. 1).

Its relief (Fig. 2) is characterised by its altitudes (alt) and slopes. Three geographic areas can be distinguished from north to south: the Sierra Morena (the natural boundary with the southern sub-plateau), the Betic plain and the Betic mountain ranges (Subbética and Penibética), which are separated by a central depression. To the west is the Guadiana river which separates Andalusia from Portugal; to the south lies the Atlantic Ocean and the Mediterranean Sea, connected through the Strait of Gibraltar; and to the east, the Mediterranean Sea and the Sierra de Segura mountain range act as the natural boundary between Andalusia and the Levante, or eastern part of Spain.

The orographic complexity of Andalusia, with extreme physical contrasts between the high mountain ranges and formations such as the Sierra Nevada (with an alt of 3483 m on the Mulhacen peak), broad plains such as the Guadalquivir river plain, and coastal areas bathed by the Atlantic and Mediterranean, all play an important role in its climatic and bioclimatic diversification. These factors, combined with the pattern of atmospheric circulation in the specific sphere of the region, the alternation of seas and continents and the thermal contrast between the Atlantic and Mediterranean, make this an area of particular interest.

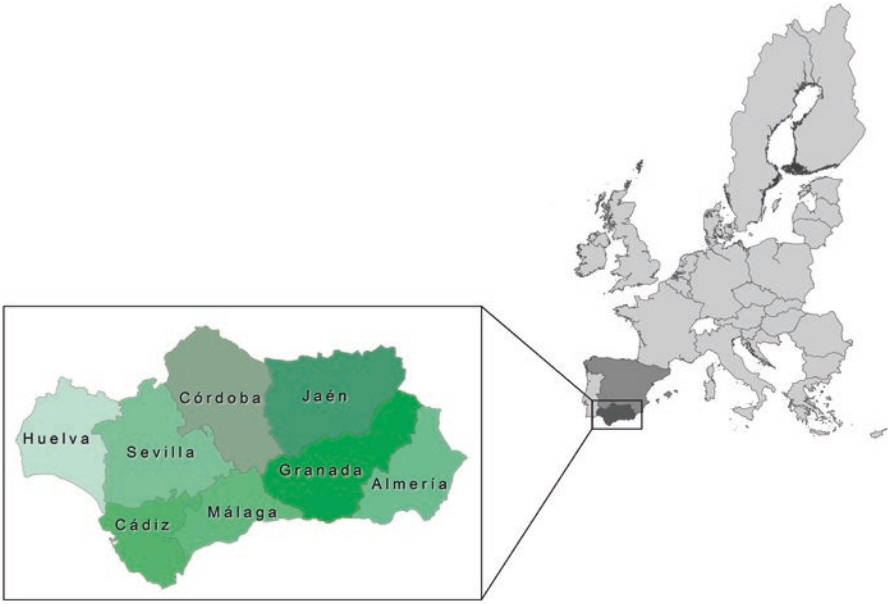

Fig. 1 Location of Andalusia

Fig. 2 Main mountain massifs in Andalusia

The study of the physical environment includes aspects of its geology and soil. The Guadalquivir valley is a sedimentary infill formed by soft materials which, with the exception of Quaternary materials, are all of marine origin. There is a particular predominance of loams and limestone loams from the Neogene-Quaternary era and allochthonous materials from the Subbética mountain ranges. In the northernmost part of the valley, there is a predominance of Triassic materials, essentially sandstone, at the expense of loams and limestone loans (tabular coverage or cover of materials).

These geological materials give rise to the formation of different soil types. The northernmost area is characterised by chromic luvisols with a nearly neutral pH, which has a direct repercussion on the flora of this specific zone. The area occupying an intermediate position in the valley is rich in marls and limestone marls, originating calcic cambisols and clay-rich vertisols, which are characteristic of agricultural soils and used essentially for the cultivation of olives and cereals. Finally, in the southernmost zone, there is a predominance of orthic solonchaks, saline-type soils enriched with gypsum and sulphated salts, which have a direct influence on the flora.

2.2 Data Processing

The data series for average temperature used in our study cover a total of 33 years, from 1975 to 2007. A key aspect of this work was the collection and review of data from a total of 2450 climate stations provided by the Department of the Environment in the Andalusian Regional Government. Initially, all thermometric or thermopluviometric stations with complete data series for the aforementioned period were selected, resulting in a total of 157 stations. Finally, after a painstaking process of data purging, any stations that did not meet the criterion of containing below 3% of gaps in relation to the total data for each station in the study period were discarded. All gaps were replaced by the mean monthly value in each time series (Rodríguez-Puebla et al. 1998; Muñoz-Díaz and Rodrigo 2004; Del Rio et al. 2012). We focussed our study on the time series from 48 weather stations (Fig. 3).

After the series selection, the data was subjected to statistical analysis (Sneyers 1992). The Shapiro-Wilk test (Shapiro and Wilk 1965) was first applied to compare the normality of the time series. We obtained the non-normal distribution of the series, which ruled out the use of parametric analytical methods. The runs test (non-parametric test) was then applied to verify the homogeneity and randomness of the data.

The trends were analysed at several scales – monthly, seasonally and annually – as this combination afforded a greater level of information (Suppiah and Hennessy 1996; Rodrigo and Trigo 2007).

The magnitude of the trends and their statistical significance (to a 95% confidence level) was obtained using the Microsoft Excel application MAKENSES (Salmi et al. 2002), with the non-parametric method of the Mann-Kendall test (Del Río et al. 2012; Robert and James 1984), in addition to Sen's test (Gilbert 1987) to determine the slope associated with the time series. Prior to the Mann-Kendall test, a pre-whitening procedure was applied exclusively to all the time series with serial autocorrelation to avoid a higher or lower estimation than the actual statistical significance shown by the trend obtained in the Mann-Kendall test.

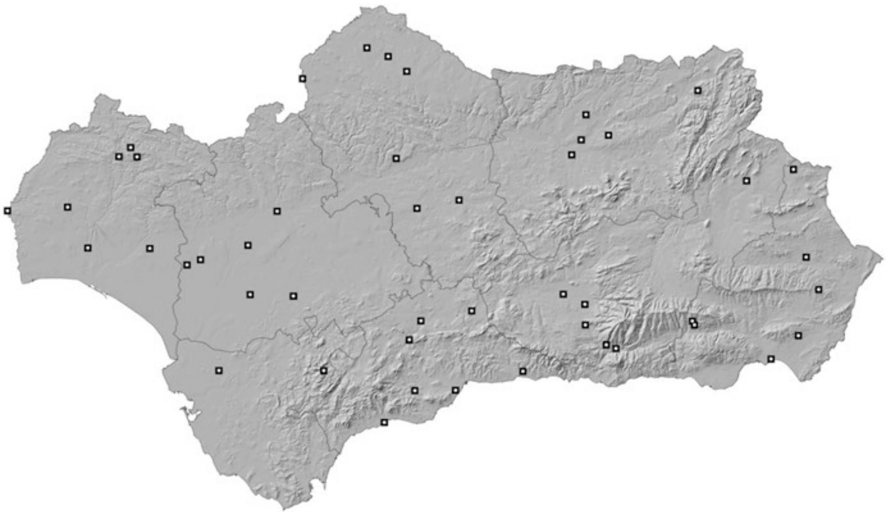

Fig. 3 Location of the weather stations in the study area

The trends were represented spatially and temporally by geo-statistical data interpolation techniques via kriging (Collins and Bolstad 1996; Johnston et al. 2001; Luna et al. 2006; Attorre et al. 2007; Cao et al. 2009; Del Río et al. 2012; Ram and Meena 2014), applied through the ArcGis© 10 programme. After several tests, it was observed that the best results were obtained from ordinary cokriging (Aznar et al. 2012) between the regression slopes (first variable) and the alt of each station (second variable), as both were spatially correlated. The exponential model had the best fit with the minimum error.

We identified the existing plant communities and important cultivation areas from the bioclimatic analysis, and particularly for olive, which is the predominant crop in Andalusia. We focussed on the farmlands in the Guadalquivir valley, an extension that is widely occupied by olive groves and to a lesser degree by almond (*Prunus dulcis*) orchards and plantations of cereal, cotton (*Gossypium* spp.) and sunflower (*Helianthus* spp.).

We followed Rivas-Martínez et al. (2002) for the description of the biogeographical units. The territory is included in the Betic, Western Iberian Mediterranean and Lusitanian-Andalusian coastal provinces, all of which have a high rate of endemism and diversity. The Betic province contains all the bioclimatic belts existing in the Mediterranean region of the Iberian Peninsula and owes its great diversity to its orology, geology and climatology. Our study covers the various biogeographical sectors, of which the Hispalense sector has the greatest territorial extension, and includes the great Guadalquivir valley, with a wide variety of materials.

Data from 48 meteorological stations were used to prepare the present bioclimatic study, selected either because they were in or near areas of olive cultivation or because they offered the greatest quantity of data. In rare cases, stations far from cultivation areas were used. Formulas of Rivas-Martínez indices were applied (1996).

Ombrothermic indices are important to agronomy, as the greater the difference between Is2 and Is3, the greater the compensation. To determine the territorial dominance of certain bioclimatic parameters such as Io, Ic and It/Itc and in order to establish the dominant thermotypes and ombrotypes, we have grouped the meteorological stations according to the number of months with vegetative activity, as the different varieties respond well to this criterion. We have divided the territory into three major areas, (a) territories with 12 months, (b) 10–11 months, and (c) 8–9 months of vegetative activity, by finding the means of these indices and obtaining the Iom, Icm and It/Itcm. We have also used crop yield data, and information on the agronomic characteristics of the varieties described by several authors such as Barranco et al. (1998) and Guerrero (1991), combining each variety with the value of the indices cited, and overlapping the crop type with each vegetation series (Rivas Martínez 1987; Cano et al. 2003b).

The various herbaceous plant associations were studied using the phytosociological methodology derived from the Braun-Blanquet (1979) Zürich-Montpellier school, subsequently modified by authors such as Géhu and Rivas-Martínez (1982). The syntaxonomical inclusion of the communities was done following Rivas-Martínez et al. (2001).

3 Results and Discussion

3.1 Analysis of Climate Trends

Figure 4 shows positive trends predominate over negative trends and are statistically more significant in the entire study territory between 1975 and 2007. This result confirms that the temperature in Andalusia has increased in the last three decades. Figure 5 shows the percentage of climate stations, obtained by the Mann-Kendall test with a confidence level of 95%.

Figure 6 shows the spatial-temporal distribution of seasonal temperature trends (°C/year) in the study territory, thanks to the application of data interpolation techniques via cokriging (Aznar et al. 2012).

At the seasonal level, the four stations can be divided into two groups. The first is the main contributor to the general upward trend observed in temperatures and comprises spring (March, April and May) and summer (June, July and August), where the percentage of stations with a positive trend is very high – 100% and 92%, respectively – and the proportion of significant stations is 92% and 85% (with a confidence level of 95%). The second group includes autumn (September, October and November) and winter (December, January and February) and is characterised by representing a percentage of stations with a more moderate positive trend of 50% and 44%, respectively, together with a marked decline in stations with statistical significance at around 27% and 15%. Although there is a prevalence of stations with a negative trend in winter, and they are distributed homogeneously in autumn, in

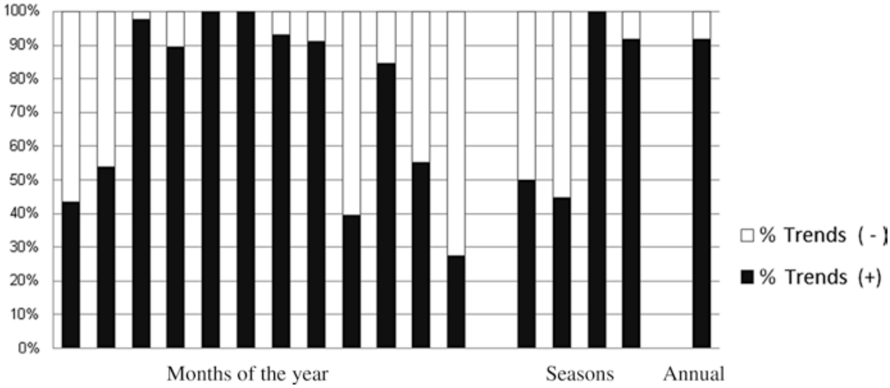

Fig. 4 Positive and negative trends in the whole of the study territory

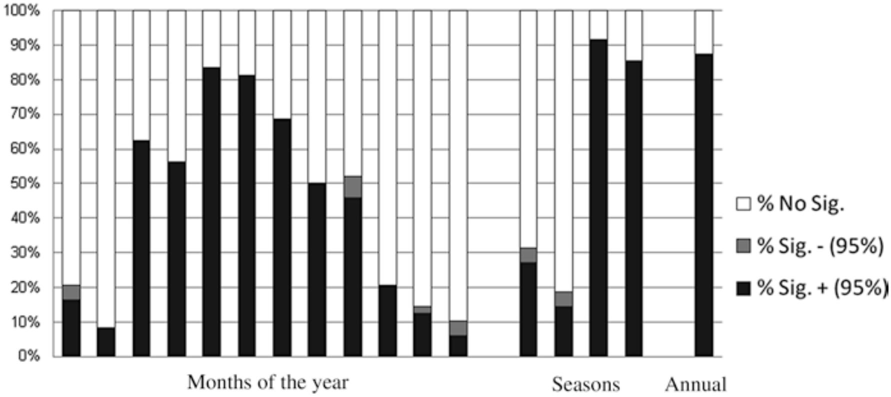

Fig. 5 Percentage of climate stations with positive and negative trends

statistical terms, and considering the total significant stations, there are more significant stations in both seasons with a positive than with a negative trend, with results of 87% compared to 13% (winter) and 78% compared to 22% (summer).

On a monthly basis, starting in winter, December has the highest percentage (86%) of stations with a significance level below 95% and the lowest percentage of significant stations with a positive trend (6%), compared to the other months in the same season and to all 12 months of the year. Most of Andalusia falls within the interval between −0.15 °C and 0.15 °C/decade in the month of December. The western half of Andalusia has areas with more acute drops in temperature, between 0.45 °C and 0.15 °C/decade in some very specific areas of the mountains to the north of Cordoba and Malaga (Antequera depression), where the decline is as much as 0.6 °C/decade. In the eastern half of the territory, although the temperature distribution is somewhat more homogeneous, some declines can be seen in the central Jaen province (Guadalquivir Valley, in the Loma de Ubeda area), in the Almanzora

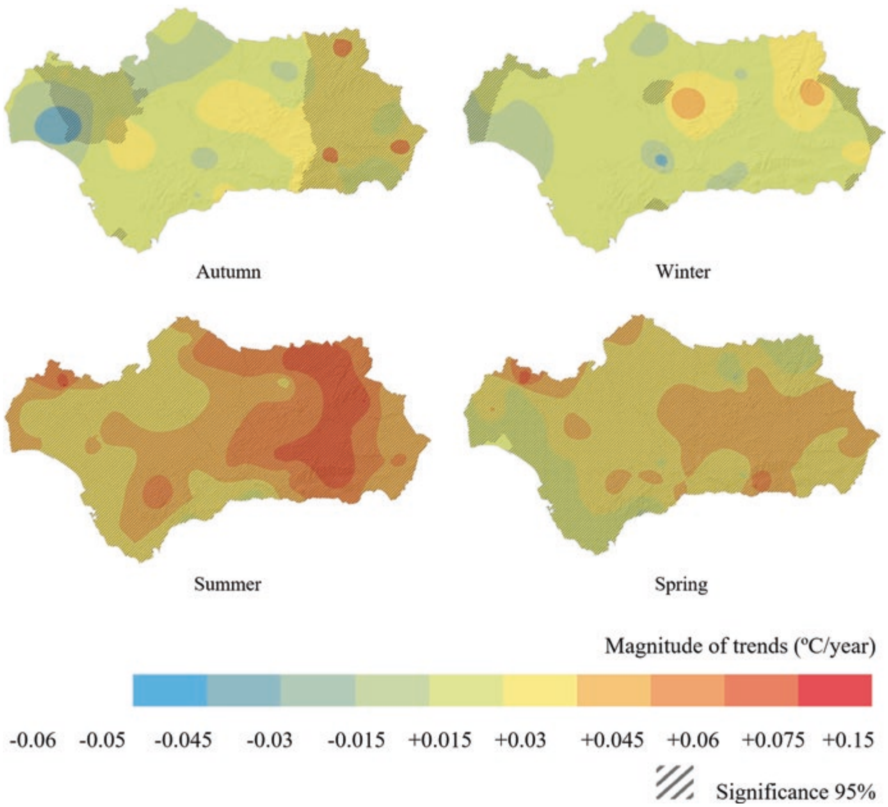

Fig. 6 Spatial distribution of seasonal temperature trends (°C/year). Magnitude of the trends (°C/year)

valley in Almería, and in Granada province, in the whole area between Sierra Nevada, the Lecrín Valley and the Sierra de Lújar mountains down to the coast. There is an increase of 0.45–0.6 °C/decade in the easternmost part of Almería (Campo de Tabernas), north of Granada, in the north-eastern part of Jaén (Cazorla, Segura and Las Villas mountains) and in the Guadalquivir Valley in the agricultural area around Cordoba.

There is a variation of −0.15 °C and 0.15 °C/decade in most of the territory in January, and some parts of the Guadalquivir Valley (central Jaén province, and the agricultural area around Huelva) have registered minimum decreases of approximately 0.47 °C/decade. The main temperature increases can be found in eastern Andalusia, with very similar magnitudes and situations to December, but covering a greater extension of territory. This expansion is particularly pronounced in the north-eastern part of Jaen (Cazorla, Segura and Las Villas mountains) and in the Guadalquivir Valley in the agricultural area around Cordoba, where the initial increase is 0.45–0.6 °C/decade, rising to 0.3–0.45 °C/decade in the peripheral areas in the easternmost part of Almería (Campo de Tabernas) and in northeast Cadiz (Sierra de Grazalema).

In January, there are still a greater percentage of stations with a negative than a positive slope but to a lesser extent than December. Another finding is the continued high percentage of non-significant stations (79%) compared to the other winter months (December and February); January has a lower percentage of non-significant stations and a higher percentage of stations with a positive significance (17%).

February is the warmest of the winter months, with 52% of the stations showing a positive temperature trend. Although there is a generalised variation between −0.15 °C and 0.15 °C/decade in most of the study territory, the greatest temperature increases, with maximums of 0.6 °C/decade, are located in the following areas, from east to west: the easternmost zone of Almería (Campo de Tabernas); north-eastern zone of Jaen (Cazorla, Segura and Las Villas mountains); the Guadalquivir Valley in the farmlands around Cordoba, descending to the area between the Antequera depression (Malaga), the Sierra de Loja and the Granada depression; and finally, northern Huelva province (Sierra de Aracena). With regard to levels of significance for this month, it is worth noting the figure of 92% for non-significant stations (the highest all winter), compared to 8% of positive significant stations.

As observed when analysing the months of December, January and February, the general trend in winter is towards a slight increase in temperatures, with some specific areas of decline, and generally very temperate winters. After several studies, numerous researchers have indicated that the temporal evolution of these temperature trends may be largely due to the influence of the North Atlantic Oscillation (Beranova and Huth 2007; Rodriguez-Fonseca and Rodriguez-Puebla 2010; Lopez-Moreno et al. 2011; Sihag et al. 2015).

In early spring, there is a clear rise in temperatures in the whole territory and a notable absence of negative trends. 97% and 90% of stations in March and April and 100% in May have a positive slope, of which 63%, 56% and 83%, respectively, are statistically significant. May is the month with the highest number of significant stations in the whole year. However, Andalusia is not the only territory in Spain to show these significant positive trends (Ordonez 2008; Brunet et al. 2009); this increase has also been registered in other studies such as those of Sigro (2004) in Catalonia; Morales et al. (2005) and Del Rio et al. (2009) in Castile-Leon; and Cruz and Lage (2006) in Galicia.

The general trend in March is a rise of 0.15–0.3 °C/decade, with a gradual increase in inland areas, mainly in eastern Andalusia (Sierra Morena, Guadalquivir Valley and the Subbética mountain ranges), at intervals of 0.3–0.45 °C/decade to a maximum of 0.98 °C/decade in the north-easternmost part of Jaen province (Cazorla, Segura and Las Villas mountains). Other maximums – although somewhat more moderate – of 0.76 °C/decade can be found in the Andaráx Valley (Almería province) as it crosses the Sierra Nevada, and in the Sierra de Aracena (northern Huelva province). Nearer the coastal zones, this rise is increasingly moderated by the influence of the sea and is less than 0.15 °C/decade at some points of the coastline, mainly in the provinces of Huelva, Malaga and Granada.

April is characterised by a general rise in temperature, although as in March, the warmest areas are found in eastern Andalusia. The greatest increase occurs in areas of the interior (Sierra Morena, Guadalquivir Valley and the Subbética mountain ranges), with intervals of 0.6 °C–0.75 °C/decade, reaching a maximum of 0.8 °C and 1 °C/decade in the north-easternmost part of Jaen province (Cazorla, Segura and Las Villas mountains) in the Guadalquivir Valley between Sierra Mágina and Sierra de Jabalcuz; in Malaga province in an area between the Antequera depression and the boundary with Granada province; and in the north of Huelva province (Sierra de Aracena). Areas with a coastal influence have registered increases that are more moderate than in inland areas but nonetheless higher than in March, revealing the smallest rises of 0.2 °C/decade, mainly in some points in the provinces of Huelva, Malaga and Granada.

May had the highest temperature increases in the whole year, with maximum values between 0.7 °C and 0.95 °C/decade, which are particularly pronounced in the eastern half of Andalusia where most of the territory has values of 0.95 °C/decade. Geographically, the areas with the greatest increases are the Subbética and Penibética mountain ranges and part of the Guadalquivir Valley to the south of the provinces of Cordoba and Seville, and the north of Cadiz province. Lesser increases of 0.26 °C/decade can be seen in the area to the northeast of Jaen province, in Seville province, between the Sierra Morena and the Guadalquivir Valley, and to the southeast of Huelva province. This downward trend is also evident in areas with a coastal influence, where the temperature gradient is between 0.4 °C and 0.26 °C/decade at some points of the coast of Almería, Granada and Malaga. May had the highest percentage of significant positive stations (83%), implying that the whole of Andalusia is undergoing a significant increase in temperature. This very high percentage is followed by June and July with 81% and 69% of significant positive stations, respectively.

Summer follows the same pattern as spring with a sustained rise in temperatures and a high percentage of significant stations with a positive trend. July and August have somewhat more instability, with some stations (6% and 8%, respectively) showing a negative trend, although not significant.

Although June is very similar to May, with 100% of stations again showing a positive trend −81% of which are statistically significant, the temperature increase is now lower and has a gradient of 0.3 °C–0.16 °C/decade in areas with a coastal influence, and around 0.6 °C/decade in areas in the interior, with maximums between 0.6 °C and 0.8 °C. However, the temperature increase falls to 0.2 °C/decade in some points in the interior such as the north-eastern zone of Jaen province (Segura, Cazorla and Las Villas mountains), and the Guadalquivir Valley as it passes through the westernmost part of Cordoba province.

In July and August, the upward temperature trend continues throughout practically the whole of the study territory, although this increase is now more moderate than in June, with values in July of around 0.15 °C–0.3 °C/decade. There are maximums of 0.5 °C/decade in some isolated areas, namely, from east to west: north of Almería province (Almanzora Valley); Granada province in the area between the Sierra Nevada and the coastal zone (Alpujarras); and the Sierra de Aracena in the north of Huelva province. Although some stations already show a negative trend these months, the percentage of statistically significant positive stations continues to be high at around 69%.

In August, the percentage of stations showing a significant positive trend falls to 50%, lower than in the previous months of May, June and July. Although the temperature trends continue to follow a general upward pattern, the increases are now more moderate, at around 0.05–0.3 °C/decade, gradually decreasing nearer the coast. Some points on the coast of Malaga province and to the south of Huelva province have decreases of −0.3 °C/decade.

During the summer months, the Atlantic coast of Andalusia, and particularly the coast of Huelva, can be observed to undergo a smaller rise in temperature than the rest of the territory; this is compared to the sharp increase in the Guadalquivir Valley, which serves as a conduit for the Atlantic influence thereby amplifying the characteristics of continentality moving inland.

The autumn months are characterised by a decline in significant stations with a positive trend. In September, there are more stations with negative than positive trends, around 60% compared to 40%, although the percentage of positive significant stations (46%) is far higher than the 6% for negative significant stations. The temperature map highlights a division in western Andalusia, which has negative general trends and a rate of decline of between 0.15 °C and 0.4 °C/decade, and three isolated zones with positive trends: the Sierra de Aracena (to the north of Huelva province), the Guadalquivir Valley in Seville province and one zone on the coast of Malaga. Eastern Andalusia is warmer and shows an upward temperature trend with increases of around 0.15 °C/decade, reaching a maximum peak of 0.4 °C/decade on the coast of Almería province.

In comparison to the other autumn months, October has the highest percentage of stations with a positive trend, 81%, while 14% have a negative trend. However, only 20% of the positive stations are significant and tend to be distributed in the eastern half of Andalusia, mainly in the provinces of Jaen, Granada and Almería. This month is warmer than September and has a mainly positive temperature trend of between −0.15 °C and + 0.3 °C/decade in most of the territory, with the sharpest increases observed in the Guadalquivir Valley, with maximums of between 0.3 °C and 0.48 °C/decade. The sharpest declines of −0.4 °C/decade can be seen in very specific areas like the central south-eastern quadrant of Huelva province and a small area in the north of Cordoba province.

In November, the temperatures once again begin to fall (44% of stations with a negative trend), although there is still a predominance of positive trends (54%), which have the highest percentage of significance: 12% compared to 2% for the total significant stations. Negative trends of 0.15–0.3 °C/decade can be seen at several points throughout Andalusia, which from east to west are north of Almería province; a small area in the centre of Jaen province; the Alhama, Tejeda and Almijara mountains (boundary with the provinces of Granada and Malaga); north of the provinces of Cordoba and Seville; and all of Huelva province with the exception of the Sierra de Aracena to the north.

Finally, the spatial pattern of annual temperature trends shows that 92% of the stations are positive, 87% are statistically significant, and there are no significant negative stations (Fig. 7). A generalised rise in temperatures can therefore be seen throughout the territory, with values of 0.15–0.3 °C/decade in the entire coastal zone

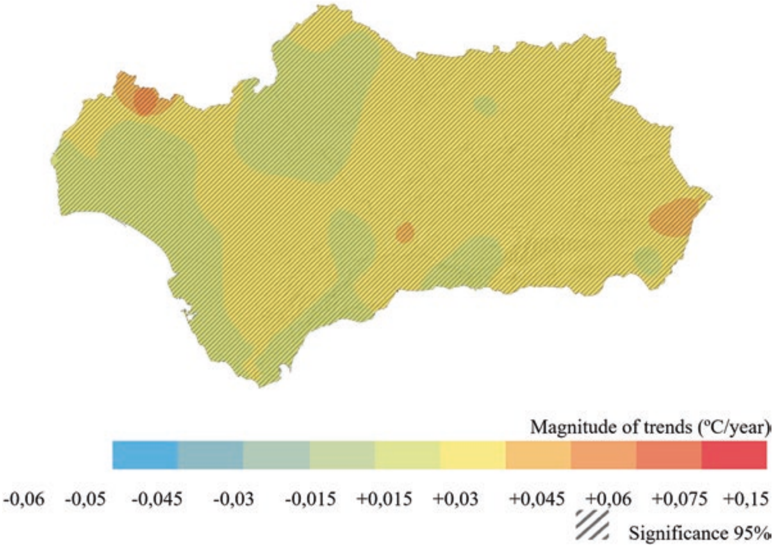

Fig. 7 Spatial distribution of temperature trends (°C/year) at the seasonal level. Magnitude of the trends (°C/year)

of western Andalusia (from Huelva to Malaga) and 0.3–0.45 °C/decade in practically all of eastern Andalusia and areas of the interior of the Guadalquivir Valley, in the area around Seville and Cadiz and in the Sierra de Aracena (Huelva). Some temperature peaks of over 0.45 °C/decade also occur in specific areas of Andalusia such as the south-easternmost part of Almería, northern Malaga and Sierra de Aracena (Huelva), which notably reaches a maximum of 0.8 °C/decade. Our results agree with numerous studies on the Iberian Peninsula which estimated an increase within the range of our values (Pausas 2004; Brunet et al. 2009 Brunet et al. 2010; Castro-Diez et al. 2007; Ileana and Castro-Diez 2010; Varma et al. 2017).

3.2 Bioclimatic Analysis

The analysis of the climatic and bioclimatic parameters reveals the following: 1) most of the territory sampled has a period of vegetative activity (PAV) of 12 months and thus undergoes no paralysis due to cold. Paralysis due to cold is understood as when the mean monthly temperature falls below 7.5 °C (Montero Burgos and Gonzalez Rebollar 1983), coinciding exactly with the territories more to the south and southwest of Jaen province, which is dominated by olive cultivation. This area has a predominantly thermo-mediterranean thermotype with an It/Itcm =346 and a dry ombrotype with values of Iom = 2.81 and Icm =19.36. Places with a PAV of 8–9 months are dominant in the northwest of Jaen province and Granada, with the particularity that both territories have an upper mesomediterranean thermotype, with It/Itcm = 264.5 and an Icm (mean value of Ic) = 19.43. However, due to the screening effect of the Segura, Las Villas and Cazorla mountains against storms, the value of Iom (mean value of Io) = 4.42, so the stations tend to have a very high Io.

The supramediterranean thermotype is highly under-represented as it contains very few areas of olive cultivation. These areas have 4–6 months of frost, so can be considered unproductive, and trees may even die due to extremely low temperatures. This occurred in 2005, when there were a very high number of days with temperatures below −10 °C, so all the crops that were not at their bioclimatic optimum froze, as occurs in upper mesomediterranean and supramediterranean areas and even in enclosed valleys when the territory behaves as upper mesomediterranean or supramediterranean due to thermal inversion. Table 1 shows there are stations with 10–11 months of PAV in the lower mesomediterranean thermotype, which occupies a large part of Jaén and Cordoba provinces, with values of Iom = 3.23 Icm =18.82 and It/Itcm =304.

The interpretation of Is2 is of particular interest in this analysis of the bioclimatic parameters that affect agriculture, and particularly olive cultivation. It has low values compared to Is3, which can be explained by the rains in June, with compensation in stations where Is3 is very high compared to Is2, thus reducing water stress. Evidently, the higher the Is3/Is2 quotient, the greater the compensation, although this does not imply that the water stress disappears, as there may be abundant rains in winter and spring but very scarce in June, proving insufficient to offset the deficit in July and August. For example, the Santiago-Pontones station has rainfall of 1148, Is2 = 0.27 and Is3 = 0.71, and a Is3/Is2 ratio = 2.62, compared to the Guadalmena Reservoir with Is2 = 0.37 and Is3 = 0.55 and a Is3/Is2 ratio = 1.48. It is important in these situations to consider another parameter of vital importance for crop management: ETP (potential evapotranspiration) and RC (soil water retention capacity), which, as noted by Cano-Ortiz et al. (2014), essentially depends on the texture, structure, organic matter and vegetation cover of the soil. (Photograph 1)

3.3 Analysis of Vegetation Cover

Until 1970, olive cultivation in Spain followed traditional lines. However, the technology revolution has enabled the implementation of a "new olive cultivation" that has persisted until the present day and receives widespread economic and social approval. It has led to an excessive use of pesticides, herbicides and phytosanitary products and had a serious environmental impact that has occasionally produced treatment-resistant insects and plants, without bringing any substantial improvement in the local inhabitants' standard of living. It has been demonstrated that the cost of using these chemical products equals or exceeds the economic advantage gained by this treatment, even before taking into account the added environmental cost, which is further aggravated by climate change. A bioclimatic treatment for territorial ordination is therefore necessary.

Sustainability can be understood as the capacity to endure over time without detriment to natural (soil, diversity, fauna) and cultural resources, applying management methods that enable constant yields and renewal. In fact, the aim of farmers is

Table 1 Bioclimatic analysis for meteorological stations with domain of olive cultivation

Station	Alt	Tm	Tmax	Tmin	P	Io	Is2	Is3	Is2/Is3	Ic	It/Itc	PAV
Andújar	212	18.1	28.3	9.2	463.9	2.13	0.17	0.28	1.66	19.1	371	12
Arjona	410	17.1	27.5	8.0	619.9	2.97	0.25	0.41	1.64	19.5	338	12
Torredonjimeno	591	16.6	27.5	7.8	648.9	3.25	0.33	0.55	1.66	19.7	329	12
Bailen	369	17.9	29.1	9.0	581.7	2.70	0.14	0.32	2.34	20.1	369	12
Jaén	510	16.9	27.4	8.6	578.3	2.85	0.20	0.40	2.00	18.8	345	12
Linares	419	17.1	26.7	8.4	642.2	3.12	0.21	0.52	2.48	18.3	339	12
La Rambla	200	15.6	25.5	7.6	527.4	2.81	0.30	0.41	1.37	17.9	308	12
Beas de Segura	577	17.1	28.3	8.3	658.0	3.20	0.30	0.58	1.93	19.7	322	12
Ubrique	332	16.3	23.8	10.2	1114.9	5.60	0.43	0.82	1.90	13.7	363	12
Jeréz de la Frontera –S. José	140	17.4	25.1	10.9	1018.2	4.87	0.20	0.41	2.05	14.2	392	12
El Campillo-Zumajo	340	16.5	26.2	9.1	802.0	4.05	0.22	0.52	2.36	17.1	347	12
Santa Barbara de la Casa	308	16.6	25.8	9.3	775.2	3.89	0.11	0.55	5.04	16.5	352	12
Posadas	88	17.7	27.4	9.0	686.9	3.23	0.30	0.50	1.66	18.4	359	12
Navas de la Concepción	434	14.3	22.6	7.1	719.7	4.19	0.26	0.63	2.42	15.5	284	12
Montoro	195	17.5	27.3	9.2	572.4	2.72	0.19	0.37	1.94	18.1	360	12
Pujerra	530	15.8	29.9	11.3	1094.7	5.77	0.60	0.63	1.05	16.1	331	12
Grazalema	823	15.3	25.2	7.5	1962.2	10.6	0.25	0.76	0.34	17.7	304	11
Baena	463	16.6	28.0	7.3	529.5	2.60	0.25	0.39	1.56	20.7	326	11
Úbeda	748	15.9	25.9	7.5	579.6	3.03	0.22	0.44	2.00	18.4	313	11
Hinojosa del Duque	549	14.8	25.1	6.7	476.9	2.68	0.42	0.68	1.61	18.4	284	11
Castro del Río	210	16.0	26.1	6.7	470.7	2.45	0.17	0.36	2.12	20.1	305	11
Granada-Aeropuerto	570	14.8	24.4	6.8	357.2	2.01	0.18	0.37	2.05	17.6	285	11
Cabra del Santo Cristo	938	14.3	24.3	6.6	449.9	2.62	0.35	0.65	1.86	17.7	275	10
Pantano Cubillas	630	15.3	25.3	7.2	525.5	2.86	0.19	0.47	2.47	18.1	297	10

(continued)

Table 1 (continued)

Station	Alt	Tm	Tmax	Tmin	P	Io	Is2	Is3	Is2/Is3	Ic	It/Itc	PAV
Cazorla ICONA	885	14.1	25.5	5.5	792.4	4.68	0.32	0.74	2.31	19.2	257	9
Antequera-El Torcal	1218	12.6	24.8	4.8	783.7	5.18	0.17	0.26	1.52	20.0	221	9
Guadix	915	14.1	24.4	6.1	320.8	1.89	0.32	0.54	1.68	18.3	264	9
Atarfe	598	13.5	24.8	5.4	401.8	2.48	0.10	0.36	2.00	19.4	243	9
Ronda-Los Quejigares	1180	10.8	22.1	3.9	1498.2	5.78	1.00	1.24	1.24	18.2	176	7
Siles-Acebeas	1320	10.7	22.2	3.4	1166.9	9.08	1.26	2.25	1.78	18.7	70.0	7

Note: *Alt* Altitude a.s.l., *Tm* Mean temperature, *Tmax* Maximum temperature, *Tmin* Minimum temperature, *P* Precipitation. Bioclimatic indices: *Io* Ombrothermic index, *Is2* and *Is3* Summer ombrothermic indices, *Ic* Continentality index (annual thermal interval), *It/Itc* Thermicity index/compensated thermicity index, *PAV* Period of Vegetative Activity.

Photograph 1 Image of the results of an agricultural plan that does not take bioclimatology into account

to abandon the criteria of maximum yield per hectare and improve the productivity of their business by managing the productive factors more effectively.

The practice of sustained olive cultivation triggers far-reaching changes, in many cases leading to a loss of biodiversity, which is now occurring on a massive scale. Until 1995, around 120 plant communities and almost 1000 plant species had been described in olive-growing areas, so olives cannot be viewed merely as another industrial crop (Cano et al. 2004; Meena et al. 2017). Olive groves are genuine ecosystems that are also home to a rich and profuse flora, some hundred or so vertebrates and a large number of invertebrate species. Another consequence of the loss of floristic biodiversity is a loss of fauna. Biological control mechanisms become affected, leading to outbreaks of insect plagues. The decline in floristic diversity is due among other causes to unsuitable tilling practices, loss of vegetation cover, lack of organic fertilisers, use of rollers (soil compaction), indiscriminate application of herbicides and, as a result, an increase in erosion and soil loss. It is therefore recommended to use agricultural practices that are not aggressive with the environment, including traditional and sustainable cultivation methods at least for marginal areas. For non-marginal high-yield areas, it is advisable to apply a mixed cultivation approach using both techniques, that is, planning the cultivation on an ecological/botanical basis while applying the "new olive cultivation" techniques which appeared in 1970, provided their administration is strictly controlled in order to minimise the environmental impact.

A crop is unproductive when the cost of production is equal to or higher than the income received by the farmer. This cost includes all the activities necessary for production, plus the environmental cost, which in most cases is not quantifiable. A crop whose cost is higher than the income it generates is considered unproductive, and even apparently productive crops using modern technology should be considered unproductive if the environmental cost is too high. Excessively high costs must be understood as any situation in which cultivation causes irreversible losses to a certain resource. However, cases of "contamination" may be permitted where the system is itself capable of self-regenerating; hence, the expression "the polluter pays" is incorrect as there may be situations involving the loss of resources on which it is impossible to place a price due to their high ecological and natural value. Cultivation at the expense of irreversible losses to soil and biodiversity and the contamination of water and land is therefore not a valid option. These issues must be considered essential when considering the implantation of a crop. All the situations described in these previous cases should be subjected to a technical agricultural reform by implementing an agricultural plan that ensures the olive orchard is maintained according to the principles listed above and is productive to the extent that crop yields may even increase. The crop may also be of better quality, as quantity and quality are compatible. This implies considering the bioclimatic aspects of the territory.

Cultivation must be planned based on respect for the environment and the optimisation of the crop in question, as all crops have an ecological and bioclimatic optimum in which the potential impact on the environment is reduced. All this requires the creation of specific agricultural and nonstandardised models that will lead to maintaining certain crops in some cases and replacing them with other more productive and less contaminating alternatives in others.

This work is grounded in the knowledge of the climate, bioclimate and wild flora as bioindicators, based on their thorough study and comparison with numerous soil analyses carried out in the same location. We can apply important treatments that offer an indispensable tool for managing different types of vegetation cover so as to maximise their benefits and encourage their use by identifying and understanding the significance of these bioindicators.

We have therefore studied the plant associations present not only from the phytosociological point of view but giving importance to soil factors and observing the correlations with the floristic-phytosociological component. We have considered the climate factors prevailing in the study areas, as they play a key role in the presence of these associations.

Plant communities on cultivated land tend to be of two types: first the "matorral" or scrub, which acts as a focus for biodiversity and an element for controlling erosion, thereby reducing soil loss by forming part of boundaries or verges, whereas the purpose of the second type, the "herbazal" or grassland, is to reduce erosion. These grasslands may be of a very different nature depending on the soil and climate characteristics. However, all plant communities can be said to act as vegetation cover and play a role in controlling erosion.

Tilling has advantages and drawbacks. Tilling is totally eliminated in this non-tilling system, and the weeds are controlled exclusively by herbicides, which are normally applied in autumn before or immediately after the emergence of the weeds. This type of non-tilling cultivation is often poorly managed. There are greater water losses due to run-off and seepage decreases, and erosion increases as there are no natural barriers to impede run-offs. It is therefore essential to manage the weeds to combat soil loss, which in turn requires soil management to mitigate some of the problems affecting the olive orchard, increase the yield and reduce the economic and environmental cost.

Other systems include mixed techniques such as semi-tilling and minimal tilling. This latter consists of tilling once or twice a year at a depth of around 5 cm in order to break the surface crust, then applying herbicides to the whole area following the non-tilling criteria. Bare soil management systems and herbicides can also be used. As we described earlier, the problem is erosion and water loss, along with loss of organic matter.

Living vegetation cover can thus be said to be beneficial. The use of vegetation cover is not new, as this technique was known to the Romans in the cultivation of vineyards and has been studied and applied since the early twentieth century. There are several types of vegetation cover: natural, artificial and seminatural. It can also be classified as inert or living cover.

Types of inert vegetation cover currently in use include shredded pruning and even straw for the purpose of increasing soil organic matter and nitrogen content which improves water retention capacity and soil structure. In general, the pruning should not be mixed with the tilled soil but left on the surface, as their continued presence on the soil ensures prolonged protection. In this case, weeds are usually controlled by herbicides. Stones are another type of inert vegetation cover that can be used, a practice that may be applied to soils with a high percentage of stoniness to protect from erosion, as the stones receive the impact of the raindrops and allow the water to seep through the soil. It is beneficial to place the stones in the lanes between the rows. Weeds must be controlled with herbicides when this technique is used.

Another category of living vegetation cover worth mentioning is spontaneous vegetation cover (natural cover), sown vegetation cover (artificial cover) and even mixed vegetation cover or a combination of spontaneous cover and sowing with gramineous or leguminous species. The difference must be observed between vegetation cover with herbaceous species and with woody and bulb species; these latter two types are undesirable as they compete strongly with the crop (Cano-Ortiz 2016). In the case of spontaneous vegetation cover, the weeds are left to emerge spontaneously (with no prior treatment) following two options: (1) allowing the vegetation cover to grow and then practising chemical or mechanical mowing; this latter is a promising technique that is not widely used except in organic crops and has advantages and drawbacks. The cover must be rigorously controlled and managed by expert staff to prevent it from becoming harmful rather than beneficial. (2) Weeds can be allowed to develop but selectively, that is, by directing or selecting the cover towards grasses, for example. This is achieved by using selective herbicides that eliminate broadleaved species (Dicotyledoneae), thus permitting the spontaneous entry of species from the genera *Lolium*, *Bromus* and *Hordeum*, and subsequently using chemical and mechanical mowing; in both cases, areas must be left that enable the seed bank to be maintained in the soil.

The alternative to natural or spontaneous vegetation is to sow one or several species of grasses such as oats, barley or rye at a dose of 50–60 kg/hectare, followed by surface raking. In cases where the slope does not allow, the best policy is to use natural cover with grasses, corrected by broadcast sowing of other grass species. Grass species are favoured because they correct erosion and contain a high quantity of lignin and humify slowly, gradually contributing small annual amounts of humus that are essential for the formation of the humus-clay complex. However, vegetation cover with Leguminosae can be achieved by sowing *Vicia*, *Trifolium*, *Lupinus* and *Medicago* which has both advantages and disadvantages. The main advantage is that the Leguminosae contribute nitrogen to the soil, leading to savings in nitrogen fertilisers; but they are rapidly absorbed into the soil, which becomes denuded in autumn and exposed to erosion. The most effective procedure is therefore to sow a mixture of leguminous and gramineous species and practice chemical or mechanical sowing before they begin to compete for water and nutrients. Small islands of terrain should be left and treated in order to ensure the maintenance of the seed bank in the soil.

Cultivation and erosion are closely related, as the extent of the erosion of the plot depends on the cultivation techniques used. Tilling is a traditional but aggressive technique, as experimentation has revealed soil losses of 20–40 tons per hectare per year, as opposed to 2.5 tons per hectare per year in plots with interspersed vegetation bands. Tilling is a long-established technique applied with the aim of increasing the availability of water by cultivating and controlling weeds. It often requires ploughing the plot several times, a practice that is counter-productive in olive orchards as it does not increase water availability but decreases the capacity of water to filter through the soil due to the presence of what are known as "suelas de labor", or heavily compacted agricultural soils caused by the repeated transit of heavy machinery.

Tilling leads to disaggregation and loss of structure, gases and organic matter. It has been demonstrated that an olive grove tilled for 10 years suffers a 30% loss of organic matter, which requires the incorporation of high doses of fertilisers to achieve acceptable yield levels. (Photograph 2)

Other effects of tilling include increased water loss through transpiration, implying a greater loss of nutrients and particularly soil loss. Erosion is aggravated not only by tilling but by specific features of the plot such as the length and gradient of the hillside, making it inadvisable to cultivate this type of plot. Erosion can be reduced through the following measures: (1) improving the filtration of water in the soil, (2) reducing the length of the run-off, (3) implementing protection measures for the soil surface and (4) carrying out conservation work. Among other conservation measures, we propose the use of organic fertilisers and living vegetation cover and suggest maintaining the herbaceous plant associations currently existing in the cultivation area.

The chemical control of weeds has caused phytocoenoses or communities of herbaceous plants to modify their floristic combination, since the elimination of certain species encourages the spread of many other invasive species. This is often due to ignorance about the use of herbicides, as chemical compounds have been

Photograph 2 Image of sustainable agriculture: a woodland pasture with olive trees and a cover of leguminous plants and grasses (Finca Peña Flor)

applied that are unsuitable for the species in question. Care should be taken when stating that all flora growing in areas of olive cultivation is harmful and therefore our enemy. Evidently, this cannot be seen as a battle between humans and what are described as "weeds", so the best policy is to identify these weeds and understand their botanical and technological behaviour in order to establish control mechanisms. (Photograph 3)

3.4 Phytosociological Analysis of Vegetation Cover in Southern Spain

The study of grassland plant communities in rainfed crops has revealed ten different types of floristic and ecological composition. These communities (plant associations) depend on the soil factor, ombrotype and thermotype, and act as an essential element in controlling erosion and water loss. They are therefore essential for combating the impacts of climate change on agriculture. These associations are *Linario sparteae-Raphanetum raphanistri* (LR), *Carduo bourgeani-Silybetum mariani* (CS), *Bromo scoparii-Hordeetum leporine* (BH), *Anacyclus clavatus-Hordeetum leporini* (AcH), *Trifolio cherleri-Taeniantheretum capitis-medusae* (TT), *Urtico urentis-Malvetum neglectae* (UM), *Fedio cornucopiae-Sinapietum albae* (FS), *Resedo albae-Chrysanthemetum coronarii* (RChr), *Papaveri rhoeadis-Diplotaxietum virgatae* (PD) and *Trifolio cherleri-Plantaginetum bellardii* (TP) (Table 2).

Photograph 3 Ecological fertilisation with fertilisers from crop residues and manure

I to V are synthetic values (Braun-Blanquet 1979). Values I to V represent the lowest and highest presence of a species in the phytosociological analytical table.

The relation between soil and vegetation is very important for plant succession, which attains its climax through the vegetation dynamic; this in turn depends on the climate and soil where it is located. A regressive succession occurs if the soil is highly degraded or has suffered powerful erosion processes (Valle 1984) either due to a loss of vegetation cover or to unsuitable cultivation techniques. In the case of intense degradation, the final stage may even be different from the ancestral optimum. This results in high water losses, and in territories with a predominance of olive cultivation such as the vast Guadalquivir Valley, positive temperature trends lead to increased ETP which threatens the crop yield. Our study on the herbaceous associations in Spain covers the following vegetation series: *Pyro bourgaeanae-Querco rotundifoliae sigmetum*, *Rhamno oleoidis-Querco rotundifoliae sigmetum*, *Myrto communis-Querco rotundifoliae sigmetum*, *Paeonio coriaceae-Querco rotundifoliae sigmetum* and *Viburno tini-Querco fagineae sigmetum*.

The association *Carduo bourgeani-Silybetum mariani* was originally described for the central Spanish plateau and has an extensive distribution. Its optimum is located in the mesomediterranean thermotype and although it can be found in the thermo- and supramediterranean thermotype. It grows on dumps, in disturbed and nitrified soils, and may even withstand a degree of temporary waterlogging. It contacts with the nitrophilous therophytic grasslands of *Hordeion leporine* (hare barley) and *Malvenion neglectae* (mallow), and in cases of prolonged waterlogging is replaced by the highly nitrophilous grasslands of *Galio aparines-Conietum maculati*. This is tall dense grassland dominated by *Silybum marianum* (milk thistle),

Table 2 Synthetic phytosociological table for some of the associations studied

Characteristic species	AcH	BH	CS	FS	LR	PD	RC	UM	TP	TT
Plantago lagopus L.	II	II								III
Bromus hordeaceus L.	II	III								V
Echium plantagineum L.		II	II				II			II
Bromus diandrus Roth s.l.	III	II	II	IV	II	II	IV	III		
Medicago polymorpha L.	III	II		III	III	III	II	II		
Calendula arvensis L.	III	II		III	III	IV	II	II		
Malva neglecta Wallr.	II		II	III	II	II	II	IV		
Erodium malacoides (L.) L'HÚr.	III			III	II	III	III	II		
Hordeum leporinum Link	V	V	III		II			II		
Sinapis alba ssp. *mairei* (H. Lindb.) Mairei	IV		II	V			III	II		
Carduus bourgaeanus Boiss. and Reuter		II	II				II			
Erodium moschatum (L.) L'HÚr.		III			II			II		
Diplotaxis catholica (L.) DC.			II			IV		III		
Malva parviflora L.			II				II	II		
Silybum marianum (L.) Gaertner			V	II			III			
Raphanus raphanistrum L.		II			V					
Chrysanthemum coronarium L.			II				V			
Lactuca serriola L.			II				III			
Anacyclus clavatus (Desf.) Pers.	III	II								
Filago lutescens Jordan	II									
Avena barbata Potter		II								
Geranium molle L.		III								
Carduus pycnocephalus L.			II							
Carthamus lanatus L.			II							
Erodium ciconium (L.) L'HÚr.			II							
Onopordum nervosum Boiss.			II							
Orlaya daucoides (L.) Greuter			II							
Scolymus maculatus L.			II							
Sisymbrium officinale (L.) Scop.			II							
Avena sterilis L.				II			III			
Lamium amplexicaule L.				II		II				
Sonchus oleraceus L.				II		II				
Carduus tenuiflorus Curtis				II						
Galium verrucosum Hudson				II						
Geranium rotundifolium L.				II						
Bromus rigidus Roth					II					II
Lolium temulentum L.					II	II				
Anagallis coerulea Schreber					II					
Anthemis arvensis L.					II					
Chrysanthemum segetum L.					II					
Linaria spartea (L.) Willd.					II					
Stellaria media (L.) Vill.						II				

(continued)

Table 2 (continued)

Characteristic species	AcH	BH	CS	FS	LR	PD	RC	UM	TP	TT
Capsella bursa-pastoris (L.) Medicus						II				
Rapistrum rugosum (L.) All.							II			
Leontodon longirostris (Finch & P.D. Sell) Talavera in Valdés & al.									III	IV
Avena barbata Pott ex Link ssp. *lusitanica* (Tab. Mor.) Romero Zarco									III	III
Trifolium cherleri L.									III	III
Vulpia myuros (L.) Gmelin									II	III
Brachypodium distachyon (L.) Beauv.									II	II
Ornithopus compressus L.									II	II
Plantago coronopus L.									II	II
Plantago bellardii All.									V	
Xolantha guttata (L.) Raf.									V	
Hypochoeris achyrophorus L.									III	
Trifolium arvense L.									II	
Brassica barrelieri (L.) Janka										II
Bromus rubens L.										II
Taeniatherum caput-medusae (L.) Nevski										III

Photograph 4 The associations *Carduo bourgeani-Silybetum mariani* and *Urtico urentis-Malvetum neglectae*

growing on dumps and in disturbed soils. It is found on soils with a mean pH of 8.189, CEC (meq/100 g) of 11.877, OOM (%) of 1.683 and a sandy texture. Some characteristic species are milk thistle, *Carduus bourgaeanus* (Italian plumeless thistle), *Carduus pycnocephalus* (Italian thistle), *Onopordum nervosum* (cotton thistle), *Scolymus maculatus* (spotted golden thistle) and *Orlaya daucoides* (flat-fruited *Orlaya*). (Photograph 4)

Mallow plant communities growing in olive groves are represented by the associations of *Urtico urentis-Malvetum neglectae*, with variable nitrophilous preferences, and presided by species such as *Malva neglecta* (dwarf mallow), *Malva parviflora* (cheeseweed) and *Urtica urens* (small nettle). It is found on manure heaps, abandoned cultivated land and land that has been overfertilised with nitrogenated compounds. This association occurs in rings around the base of olive trees. It is widely distributed in the mid-European Atlantic Montane and Mediterranean areas in the mesomediterranean thermotype and may extend as far as the supramediterranean. This community is dominated by dwarf mallow or cheeseweed and sometimes by both, as the two species may coexist. There is a lesser presence of small nettle. Although the samples reveal a predominance of cheeseweed, which could be ascribed to *Sisymbrio-Malvetum parviflorae*, there are no ecological, floristic or biogeographical differences to support this syntaxon, so it could be synonymised to *Urtico urentis-Malvetum neglectae*, an association with a minimum area of 2 m^2 and a species richness of 7–16 species. The soil analysis reveals lower values for the soil parameters than for *Resedo-Chrysantemetum coronari*. However, the exchange capacity is 10.889 meq/100 g with a high value of assimilable phosphorus of 36.190 ppm, a sandy texture, 1.698 meq/100 g of exchangeable Mg, 1.266 meq/100 g of exchangeable K, an OOM of 1.904% and total nitrogen of 0.179%. The data identify communities of *Malva* as bioindicators of soil nitrogen content and of certain mineral ions such as K, Mg and P. Some characteristic species are small nettle, dwarf mallow, cheeseweed and *Diplotaxis catholica* (Table 3).

Galactito tomentosae-Vulpietum membranaceae is a community with high cover and a subnitrophilous and thermophilous character. It develops in late spring and disappears in early summer and is dominated by the species *Galactites tomentosa*, *Vulpia geniculata*, *Andryala integrifolia*, *Leontodon taraxacoides* and *Echium plantagineum*. It tends to be present in soils with the following mean values: pH of 6.19; CEC (meq/100 g) of 11.109; OOM (%) of 1.293 and P (ppm) of 7.3. It has a sandy-silty texture and medium RC. Some characteristic species are *G. tomentosa*, *V. geniculata*, *A. integrifolia*, *L. taraxacoides*, *E. plantagineum*, *Gaudinia fragilis*, *Crepis vesicaria* and *Chamaemelum mixtum*.

The grasslands of *Trifolio cherleri-Taeniatherum capitis-medusae* are found on abandoned cultivated lands and the verges of paths and have a subnitrophilous character. They have their optimum in the meso- and supramediterranean belt in the Carpetan-Iberian-Leonese sector and are also very well represented in the Mariánico-Monchiquensian and Toledano-Tagano sectors of the Lusitanian-Extremaduran subprovince. Towards more nitrified environments, these grasslands contact with communities of *Hordeum leporinum*. They are located in soils with the following mean values: pH of 6.13; OOM (%) of 1.45; CEC (meq/100 g) of 9.63; P (ppm) of 5.11; they have a mainly sandy texture as a result of their low RC. These soil values are very similar to those of *Trifolio cherleri-Plantaginetum bellardii*, and there is a frequent presence of the companion species of this latter association, pointing to the strong dynamic between them. Some characteristic species are *Taeniatherum caput-medusae*, *Avena barbata* sp. *lusitanica*, *Trifolium cherleri*, *Plantago lagopus*, *E. plantagineum* and *Bromus rubens*.

Very similar to the subnitrophilous grasslands is the association *Plantagini bellardii-Aegilopetum geniculatae*, which is typical of less ruderal environments than *Hordeion leporini*. It is generally found in olive groves that have been fertilised for extended periods and in shrubland clearings with lower nitrogen content than the communities of *Hordeion leporini*. The substrates are decarbonated marmoreal

Table 3 Soil parameters of the herbaceous communities in the study

	AcH	ArH	BH	LR	PD	ArP	ArChr	RChr	UM	PA	TT
CEC	15.365	9.131	10.544	6.661	14.304	10.869	12.328	11.68	10.889	10.54	9.63
OOM	1.541	1.56	1.667	0.75	1.02	1.803	1.622	1.574	1.904	1.8	1.458
Nt	0.115	0.102	0.133	0.064	0.09	0.14	0.105	0.129	0.179	0.136	0.084
Pa	9.789	13.957	15.4	4.824	15.35	14.722	26.9	20.95	36.19	5.605	5.111
Mgc	1.683	1.856	1.068	0.835	2.351	1.864	2.131	2.716	1.698	1.713	1.097
Kc	0.79	0.256	0.375	0.259	1.002	0.412	0.698	1.476	1.266	0.206	0.156
pF 15 atm	15.322	8.613	8.203	7.366	19.117	13.001	11.975	14.24	13.197	11.82	6.673
Tx arc	17.758	19.78	14.503	17.28	40.015	25.394	19.763	24.24	21.293	25.83	13.59
Tx ar	20.448	62.411	54.254	64.238	19.986	45.694	55.826	37.85	46.001	44.98	64.93
Tx lim	61.794	17.803	31.245	18.51	40	28.906	24.413	37.94	32.712	29.2	21.49
CE	0.355	0.209	0.122	0.211	0.286	0.162	0.193	0.491	0.565	0.105	0.049
pH	8.275	7.43	7.475	6.616	8.085	7.633	7.77	7.943	7.776	7.581	6.13

Note: *CEC* cation exchange capacity in meq/100 g, *OOM* oxidisable organic matter in %, *Nt* total nitrogen in %, *Pa* assimilable phosphorous in ppm, *Mgc* exchangeable magnesium in meq/100 g, *Kc* exchangeable potassium in meq/100 g, *pF 15 atm* pressure at 15 atmospheres (water retention capacity) in %, *Tx arc* clayey texture in %, *Tx ar* sandy texture in %, *Tx lim* silty texture in %, pH

AcH *Anacyclo clavati-Hordeetum leporine*, ArH *Anacyclo radiati-Hordeetum leporinii*, BH *Bromo scoparii-Hordeetum leporinii,* LR Linario sparteae-*Raphanetum raphanistri*, PD Papaveri rhoeadis-*Diplotaxietum virgatae*, ArP *Anacyclo radiati-Papaveretum rhoeadis*, ArChr *Anacyclo radiati-Chrysanthemetum coronarii,* RChr *Resedo albae-Chrysanthemetum coronarii*, UM *Urtico urentis-Malvetum neglectae*, PA *Plantagini bellardii-Aegilopetum geniculatae,* TT *Trifolio cherleri-Taeniatheretum capitis-medusae* (Cano-Ortiz 2007) limestones with a close to neutral pH. The subnitrophilous grassland of *Aegilops geniculata* is differentiated from *Trifolio cherleri-Taeniatheretum capitis-medusae*, with a siliceous character, due to the presence of basophilic elements such as *Medicago minima*, *Atractylis cancellata*, *Polygala monspeliaca*, *Velezia rigida* and others. It is differentiated from *Medicago rigidulae-Aegilopetum geniculatae* as it includes siliceous elements such as *Plantago bellardii* and *Trifolium subterraneum*. We therefore propose the association *Plantago bellardii-Aegilopetum geniculatae*, which grows on decarbonated substrates and substrates with little sun in mesomediterranean thermotypes and dry subhumid ombrotypes. In sunny and warmer exposures, this grassland gives way to the community of *Aegilopo neglectae-Stipetum capensis*. It grows in all Lusitanian-Extremaduran calcareous sites (Portugal and Spain) within the series *Lonicero implexae-Querco rotundifolaie sigmetum*. It is characterised by growing on soils with the following mean values: pH of 7.581, OOM (%) of 1.8 and CEC (meq/100 g) of 10.53; it has a mainly sandy texture. Some characteristic species are *Aegilops geniculata*, *Trifolium stellatum*, *M. minima*, *A. triuncialis* and *T. scabrum*. In all cases, the characteristic species have their soil optimum in the soil values obtained for each plant community.

The association of herbaceous therophytes with a spring phenology is represented by *Fedio cornucopiae-Sinapietum albae* and is present in newly tilled loamy soils used mainly for olive cultivation. It is distributed in the Betic region in the thermo- and mesomediterranean thermotype and reaches its optimum in the olive groves on farmlands in the Guadalquivir area, where it forms monospecific communities of *Sinapis alba* subsp. *mairei*, on soils with a silty-clayey texture. It can grow to heights of 1.70 m and attain coverage of 100%. We have studied the soil factors that condition the presence of this association, although these are not the only influence on the location of *Fedio-Sinapietum mairei*, as *Sinapis alba* subsp. *mairei* also responds to temperature. This explains why it is located in the area of *Paeonio-Quercetum rotundifolia*, a thermophilous variation with *Pistacia lentiscus*, and *Rhamno-Quercetum rotundifoliae*, a grassland association included in the thermophilous alliance *Cerintho majoris-Fedion cornucopiae* (Rivas-Martinez et al. 2001). The grassland of *Fedio-Sinapietum* appears relatively frequently in olive groves on gypsum loams. The soil salinity test reveals a mean value of 0.690 mmhos/cm, with a minimum value of 0.24 and a maximum of 2.60, compared to the mean value of 0.27 mmhos/cm, minimum of 0.20 and maximum of 0.37 for *Papaveri-Diplotaxietum virgatae*. It can therefore be said that *Fedio-Sinapietum mairei* requires soils with a greater salt content than *Papaveri-Diplotaxietum virgatae*. Some characteristic species are *Sinapis alba* subspecies *mairei*, *B. diandrus*, *M. polymorpha*, *Erodium malacoides*, *Calendula arvensis*, dwarf mallow and *Fedia cornucopiae*. (Photograph 5)

The nitrophilous communities dominated by *Hordeum leporinum* have their optimum in the meso- and supramediterranean thermotypes. The association *Bromo scoparii-Hordeetum leporini* has a therophytic character and a spring phenology and has been described for continentalised environments in central Spain (Rivas-Martínez 1978; Datta et al. 2017). It has the following catenal contacts: towards less nitrified and drier soils, it contacts with grasslands of *Taeniethero-Aegilopion*

Photograph 5 The associations *Fedio cornucopiae-Sinapietum albae* and *Bromo scoparii-Hordeetum leporini*

geniculatae, where there is more moisture, with grasslands of *Agrostion salmanticae*, and towards more nitrified zones, with grasslands of mallow. It grows in soils with the following mean values: pH of 7.47; OOM (%) of 1.667; CEC (meq/100 g) of 10.544; P (ppm) of 15.40, with a mainly sandy texture and a medium RC. Some characteristic species are *H. leporinum*, *Geranium molle*, *B. hordeaceus*, *Erodium moschatum*, *Raphanus raphanistrum*, *M. polymorpha* and *Plantago lagopus*. However, *H. leporinum* is a grass that also becomes dominant in the thermo-mediterranean thermotype where it shares an ecological niche with other differential species. The following have therefore been described in these latter territories: the association *Anacyclo radiati-Hordeetum leporini*; a western thermo-mediterranean association frequent in ruderalised environments, on verges of paths, roadsides and near old houses and dumps where there is a predominance of *Anacyclus radiatus* and *H. leporinum*. It has been described for the centre-south of Portugal and southeast Andalusia (Spain) and is dominated by *H. leporinum* and *A. radiatus*. This latter species prefers neutral-basic soils and thermophilous environments and thus does not extend to the upper Guadalquivir but is limited to the south-western Iberian Peninsula (Rivas-Martínez 1978). It occurs in soils with the following mean values, pH of 7.430, CEC (meq/100 g) of 9.13, OOM (%) of 1.56 and P (ppm) of 13.957, with a mainly sandy texture and a medium RC. Some characteristic species are *H. leporinum*, *A. radiatus*, *Plantago lagopus*, *Echium plantagineum*, *Avena fatua*, *Hedypnois cretica* and *B. rigidus*.

The Guadalquivir (Hispalense sector) and Subbética territories are home to grassland of *H. leporinum* that belongs to the association *Anacyclo clavati-Hordeetum leporini*, which occurs on basic substrates with a pH over 8. These grasslands frequently contain basophilic species such as *M. minima*, *Sinapis alba* subsp. *mairei*, *Moricandia arvensis*, *Centaurea pullata* and *Plantago albicans*, absent from *Bromo scoparii-Hordeetum leporini*, described for the continentalised zones of the plateau. There is a frequent presence of *A. clavatus*, which, although it is indifferent in soil terms, prefers basic substrates, and an absence of *A. radiatus*, a thermophilous element that does not extend as far as the upper Guadalquivir. This association is perfectly differentiated from *Bromo scoparii-Hordeetum leporini* and *Anacyclo radiati-Hordeetum leporini* in the statistical analysis. The syntaxon is distributed in dry subhumid mesomediterranean areas in Betic territories and grows in the area of the series *Paeonio-Querco rotundifoliae sigmetum* and *Viburno tini-Querco fagineae sigmetum*, occupying soils with a high value of CEC 15.3, pH of over 8, OOM of 1.54 and with a sandy-silty, clayey-silty texture and hence a medium RC.

The association *Anacyclo radiati-Chrysanthemetum coronarii* is characteristic of ruderalised environments such as the verges of paths and roadsides in the southwest of the Iberian Peninsula. There is a presence of *A. radiatus* and *Chrysanthemum coronarium var. concolor*, absent from the association *Resedo albae-Chrysanthemetum coronarii*, a community described for the Levantine and Balearic territories. The grassland proposed by Cano-Ortiz et al. (2009) grows in Lusitanian-Extremaduran territories on pH-neutral substrates with a high content in organic matter. Rivas-Martínez (1978) published the *Anacyclo radiati-Hordeetum leporini* subassociation *Chrysanthemetosum coronarii* for cases where the grassland of *H. leporinum* in the southwest of the peninsula presents *Chrysanthemum coronarium* (Cano et al. 2017; Yadav et al. 2017).

The differences in soil and structure, coupled with the frequent presence of *Chrysanthemum coronarium* var. *discolor* and var. *concolor*, led us in previous studies to propose a change in status and to raise the subassociation *Chrysanthemetosum coronarii* to the rank of association. It is dynamically derived from *Anacyclo radiati-Hordeetum leporini*, from which it is differentiated floristically and ecologically, as the soils conducive to *Anacyclo-Chrysanthemetum* have higher mean values of CEC, OOM, assimilable P, K, etc. than the soils of the association *Anacyclo radiati-Hordeetum leporini*. This association is found growing on soils with a mean pH of 7.77, OOM (%) of 1.6, and a mainly sandy texture. Some characteristic species are

A. radiatus, *H. leporinum*, *A. fatua*, *Lactuca serriola*, *Beta vulgaris* subsp. *maritima* and *Chrysanthemum coronarium* var. *discolor* and var. *concolor*.

The association *Resedo albae-Chrysanthemetum coronarii* grows under thermo- and mesomediterranean thermotypes in a subhumid climate. This community has nitrophilous preferences and is found on dumps. It is ruderal in nature and contacts towards more nitrified zones with formations of *Carduo-Silybetum mariani*. This grassland has a high degree of cover and a dominant species, *Chrysanthemum coronarium* that can grow to heights of 2 m, with a minimum area of 1 m^2. It has a floristic richness of 9–23 species per relevé. The presence of dwarf mallow, cheeseweed, milk thistle, *C. pycnocephalus*, *C. bourgaeanus* and cotton thistle points to a nitrophilous variant within the association. It is unsurprising that the soil study reveals high values of OOM of 1.574% and total nitrogen of 0.129% for this association, a CEC of 11.677 meq/100 g, and high values of exchangeable Mg with 2.716 meq/100 g and 1.476 meq/100 g of exchangeable K. It has a sandy-silty texture, so the RC decreases as these soils have pF15 atmospheres of 14.238%. The soil analysis shows there are insufficient differences to justify maintaining this association within the alliance *Hordeion leporini*, as its organic matter and total nitrogen values are closer to mallow; furthermore, the association has a physiognomy and structure that aligns it more closely with mallow, and there is a frequent presence of species in the genus *Malva* in the communities of *Chrysanthemum coronarium*. This may explain why the statistical study shows a combination of relevés of *Resedo-Chrysanthemetum* and *Urtico-Malventum*, possibly due to the fact that the mean values of the different soil parameters are very similar in both associations (Cano-Ortiz et al. 2014). Some characteristic species are *Chrysanthemum coronarium*, *B. diandrus*, *Erodium malacoides*, *A. sterilis*, *Lactuca serriola* and cheeseweed. (Photograph 6)

The grasslands of *Papaver* and *Diplotaxis* have been included in two associations. The first is a ruderal community in lower thermo-mesomediterranean territories with a dry subhumid ombrotype. The community of *Papaver rhoeas* and *Anacyclus radiatus* prefers more disturbed soils with lower organic matter content than the previous community. The presence of thermophilous elements differentiates this community from common poppy-*Diplotaxietum virgatae* which has a more

Photograph 6 The associations *Resedo-Chrysanthemetum coronarii* and common poppy-*Diplotaxietum virgatae*

continental character and has been described for the central Iberian Peninsula (Rivas-Martínez 1978). Cano-Ortiz et al. (2009) therefore proposed the association *Anacyclo radiati-Papaveretum rhoeadis*, which is dominated by *Papaver rhoeas* and *A. radiatus*, and located on soils with a pH of 7.6, OOM (%) of 1.8 and a mainly sandy-silty texture. The RC is medium. Some characteristic species are *P. rhoeas*, *P. dubium*, *Lolium rigidum*, *A. radiatus*, *P. hybridum* and *M. polymorpha*.

The second herbaceous community belongs to the association common poppy-*Diplotaxietum virgatae* and is a grassland distributed throughout the Manchegan, Lusitanian-Extremaduran and Betic mesomediterranean territories. This community has a spring character and is characteristic of disturbed nitrified soils, roadsides and verges of paths and grows in rainfed crops, olive groves, vineyards and areas of cereal cultivation, among others. Our samples were always taken on basic soils with a pH of 7.9–8.3; these grasslands are located on salt-poor soils and particularly on soils with higher clay content. From the floristic point of view, they may resemble the community of *Diplotaxis catholica* or *D. virgata*, which we interpret as the same community, as there are no synecological differences between the relevés dominated by either of the two species. This is more likely to be a fragmentation due to the indiscriminate use of herbicides. The minimum area obtained is 2 m^2, and the floristic richness is 8–18 species per relevé. These grasslands occur alongside those of *Sinapis alba* subsp. *mairei*, with which they contact catenally, and into which they transition as the salt concentration increases and the clay content and hence the CEC decreases. Further from thermophilous environments, there is a decline in *Sinapis alba* subsp. *mairei* and the grassland is enriched with species from the genus *Diplotaxis*, so *Papaveri-Diplotaxietum virgatae* occupies the areas of *Paeonio-Quercetum rotundifoliae typicum*, *Asparago acutifolii-Quercetum rotundifoliae* and *Pyro-Quercetum rotundifoliae*. These grasslands are included in the alliance *Hordeion leporini* (Rivas-Martínez et al. 2001; Meena et al. 2014). The statistical analyses conducted on the relevés collected in the Guadalquivir Valley and the originals show them as separated in the cluster (Cano-Ortiz et al. 2014), possibly due to the presence of thermophilous elements and to certain endemisms such as *Anchusa puechii* and *Arenaria hispanica* which are absent from the original table. This suggests the existence of a new syntaxon for loams in the Guadalquivir with a mesomediterranean thermotype and a dry ombrotype in the Hispalense sector, in the area of the series *Paeonio-Querco rotundifoliae sigmetum*. This association is characterised by growing on soils with a mean value of OOM of 1.02, CEC of 14.30 and pH of 8.08. It has a silty-clayey texture and therefore a high RC. Some characteristic species are *D. católica*, *M. polymorpha*, *C. arvensis*, *E. malacoides*, dwarf mallow, *Lamium amplexicaule* and *B. diandrus*.

In olive groves on Triassic materials with a neutral character, there is a grassland with a high degree of cover whose dominant species is *Raphanus raphanistrum*, which may ultimately reach a maximum height of 1.20 m. It has been described as a community of *Linaria spartea* and *R. raphanistrum* by Cano-Ortiz et al. (2013). This community has an early spring phenology and is found in the thermo- and lower mesomediterranean thermotype in the Hispalense, northern and Mariánico-Monchiquensian territories. This grassland is clearly differentiated from the rest of the associations in the study due to its different floristic composition and synecology. It has a minimum area of 2 m^2 and a floristic richness of 10–17 species per relevé. The soil analysis reveals the existence of acid or base-poor soils. It occurs throughout the entire length of the Guadalquivir Valley, which contacts with the siliceous materials of the Sierra Morena. The neutral-basophilic community of *Raphanus raphanistrum* should therefore be included within the acid-neutrophilous faciation of the series *Rhamno-Querco rotundifoliae sigmetum* and the acid-neutrophilous faciation of *Paeonio-Querco rotundifoliae*. Its ecological and floristic characteristics mean we can establish the new association toadflax-*Raphanetum raphanistri* Cano-Ortiz, del Río, Pinto Gomes ass. nova hoc loco within the alliance *Hordeion leporini* (Table 2 rel. 1–24, typus rel. 1 in Cano-Ortiz et al. 2013). This association was not typified according to the stipulations of the international code of phytosociological nomenclature and is therefore typified here. The plant community name is typified considering the code of phytosociological nomenclature, since Cano Ortiz et al. (2013) provide a table of plant communities without specifying the name of the plant association, making it necessary to propose a type relevé.

Some characteristic species are *M. polymorpha*, *H. leporinum*, *B. diandrus*, *L. amethystea*, *L. spartea*, *Brassica barrelieri* and *R. raphanistrum*. (Photograph 7)

Finally, the non-nitrified grassland of *Trifolio cherleri-Plantaginetum bellardii* grows in spring on thin soils that are not very intensively grazed. It has its optimum in the Lusitanian-Extremaduran sector. This association has an early phenology and scarce biomass and grows in dry subhumid environments in Lusitanian-Extremaduran territories. It is characterised by low-growing therophytic species with a low degree of cover. This association is characterised by soils with the following mean values, pH of 6.04, CEC (meq/100 g) of 5.21, OOM (%) of 1.569 and P (ppm) of 5.26, with a sandy texture and low RC. Some characteristic species are *Xolantha guttata* (European frostweed), *Plantago bellardii* (hairy *plantain*),

Photograph 7 *Linaria spartea-Raphanetum raphanistri*

Hypochaeris achyrophorus (Mediterranean catsear), *Ornithopus compressus* (yellow serradella) and *Filago pyramidata* (*broadleaf cottonrose*).

4 Conclusions

Positive trends have clearly prevailed over negative ones in recent decades. Spring shows the highest significant positive trend, and there is a certain decline in winter, which is not the season that contributes most to the generally observed warming trend. Temperatures have undergone a significant increase in Andalusia. The greatest rise can be seen in May and June, with slightly more moderate rises in April and July. The trend with the highest magnitude was found in May (0.7–0.95 °C/decade). The areas in Andalusia that have seen the sharpest rise in temperature are the zone between the Guadalquivir Valley and the Subbética mountain ranges (mainly in the provinces of Cordoba and Jaén), the Aracena range to the north of Huelva province and the easternmost area of Almería province. Annual temperatures have raised 0.15–0.45 °C/decade, with 87% stations significant. Spring and summer are the seasons that contribute most to these annual trends. Our findings point to positive and negative temperature trends in Andalusia. Positive trends prevail in the Guadalquivir Valley, an area dominated by agricultural production and particularly areas of olive cultivation.

The consequences of climate change for agriculture – specifically in Andalusia – are becoming catastrophic, as the irregular temperatures and rainfall affect crops and cause losses in yields, a situation that is further aggravated by intensive cultivation practices using misguided agricultural techniques. The bioclimatic location of the crops and the use of an appropriate vegetation cover for olive groves are two important techniques for mitigating climate change. It is therefore essential to implement an agricultural ordination based on the knowledge of the climate in a territory and to use vegetation cover to mitigate the sharp rises in temperature and reduce evapotranspiration as part of a policy of sustainable development.

5 Future Prospectus

Demonstrated the positive trends of temperature in Europe, and in particular in the Guadalquivir valley, together with an irregular distribution of rainfall, and an increase in evapotranspiration and drought (Skarbit et al. 2018; García Barrón et al. 2018; Spinoni et al. 2018; Kumar et al. 2018). Based on the bioclimatic classification of Rivas-Martínez and Loidi (1999), as in that classification the temperature parameter intervenes, there is a bioclimatic tendency parallel to the climatic tendency, in which the mesomediterranean thermocline tends to the thermo-mediterranean, with the consequent entry of thermophilic species, some of which can be used to create vegetation cover

We are currently resampling the plant associations sampled in previous years in order to determine their state of conservation and propose regeneration models, since plant cover mitigates climate change. In the future, we expect to obtain a set of species that are more or less favoured by climate change and which can be used for plant cover to mitigate climate disasters.

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Abiotic Stress in Agricultural Crops Under Climatic Conditions

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Abstract

Crop stress has been identified as one of the problems that threaten global food security. Crop stress is an injurious deviation from the normal physiological processes that result into a decline in crop yields. It could be due to biotic factors (biotic stress, i.e. insect pests and disease pathogens) or abiotic factors (abiotic stress, i.e. drought, flooding, radiation and nutrient deficiencies). Agricultural crops normally undergo series of physiological processes (photosynthesis, respiration, stomatal functions and nutrition) during developmental stages of their life cycles that are sensitive to environmental conditions. The stressed environmental impact on the crops during growth and development leads to biochemical and morphological modifications in plant species. This chapter details the predominantly occurring abiotic stresses of crops that are directly or indirectly associated with the disruption of the normal growth and developmental processes in crops. The effects of abiotic stress in plants range from the qualitative and quantitative changes in the synthesis of type of proteins in crops to the disruption of the flower bud formation and pollination process in plant, as well as impaired nutrient uptake resulting in poor crop yields. About 51–82% crop yield in world agriculture is lost annually due to abiotic stress. The mechanisms of the four principal abiotic stresses (temperature, water, radiation, nutrients, etc.) are presented in the chapter. An understanding of the mechanisms of abiotic stress in agricultural crops could help farmers to optimize the crop productivity under the changing climate. This chapter therefore focuses on causes of the abiotic stresses affecting world food crops, their effects and possible stress coping strategies to promote global food sufficiency.

Keywords

Drought · Temperature stress · Heat stress · Nutrient imbalance · Climate change

Abbreviations

ABA	Abscisic acid
ACC	1-Aminocyclopropane-1-carboxylate
C4	4-Carbon sugar compound
Ca	Calcium
CO_2	Carbon dioxide
K	Potassium
Mg	Magnesium
N	Nitrogen
NA	Nucleic acids
P	Phosphorus
QTL	Quantitative trait loci
ROS	Reactive oxygen species
UV	Ultraviolet

1 Introduction

Over the years, agricultural production has been greatly affected by the effects of changing climate. The climate change and its mitigation strategies have increasingly gained tremendous attention over the last decades as a result of its increasing influence on agriculture. Agricultural crops normally go through a cycle that is very sensitive to the environment at their growth and developmental stages (Hartfield and Prueger 2015). This implies that stress at any developmental phase is usually injurious to the performance of crop over the production period. Zhu (2016) observed that agricultural crops are consistently cultivated under constantly changing environmental conditions, which are usually unfavourable for their growth and development. These negative effects on crops are termed as crop stress.

Crop stress refers to any external factor that leads to a malfunction in the life cycle of agricultural crops. In other words, crop stress can be defined as anything that reduces crop yield from attaining its highest obtainable maximum yield. Stress is like a sickness to an agricultural crop which derails it from its normal healthy state of growth and development. Agricultural stress represents the injurious deviation from the normal endogenic to exogenic processes in plants. It could be directly or indirectly responsible for the disruption from the normal physiological processes and functions in the plant (Patakas 2012; Hartfield and Prueger 2015; Mantri et al. 2012; Meena et al. 2016).

The two types of crop stress are biotic and abiotic. Biotic stress includes infections from disease pathogens and physical attacks from herbivores, while abiotic stress includes drought, nutrient imbalance, salinity, nutrient toxicity, water inadequacy or waterlogging conditions, etc. Plant stress imposes significant shortfalls in the yield of crops for each cropping season. Hence, there is a need to identify these various crop stresses in order to establish coping mechanisms for them in view of boosting crop production. This chapter will however focus mainly on abiotic stress of agricultural crops as they are more influenced by the changing climate. It is highly imperative to understand abiotic stress factors that have been induced and motivated by variations in climatic conditions in order to institute coping/mitigation/resistance strategies aimed at improving crop growth, development and yield. Ahmad and Prasad (2012) reckoned that as climate change occurs, plants respond to varying prevailing climatic conditions and these changes (which are mostly abiotic stress) also influence the soil-plant-atmosphere continuum upon which the yield of every crop across the globe is dependent on for survival. Mantri et al. (2012) maintained that predominantly occurring abiotic stresses of plants such as drought, heat, salinity and cold adversely affect up to 70% of the survival biomass production and yield of most staple food crops on the globe.

Jenks and Hasegawa (2005) reported that the arguable pertinence of abiotic stress in agricultural crops lays on the fact that they produce the bulk of limitations to crop cultivation in world agriculture. Furthermore, about 51–82% of annual obtainable crop yield in world agriculture is usually lost due to effects induced by environmental or abiotic stress (Mantri et al. 2012). While assessing climate change impacts on the production of wheat (*Triticum* spp.) in Iran, Valizadeh et al. (2014)

noted that the grain yield of wheat will decrease from about 4500 kg ha^{-1} to 3500 kg ha^{-1} if the climatic factors of temperature and rainfall variability are not adequately mitigated to support crop cultivation. Similarly, Vijayalakshmi (2018) observed that global grain production overtime has reduced by the significant part of more than 5% due to drought stress. Edmeades et al. (1992) also earlier documented a 17% decrease in annual yields of grains owing to drought stress effects. In West Africa, the groundwater table has been significantly reduced over time, and consequently, well water has become a challenging alternative water source for the rural dwellers (Akinci and Losel 2012). Reduction in well water has limited irrigation-based agriculture, especially during the dry season. In Nigeria, rainfall occurs in certain periods of the year, which has limited crop cultivation to a particular period of the year. For instance, the savannah region of Nigeria has only one growing season, while the rainforest has two growing seasons (Ejiogu and Offor 2009). Water stress plays a significant role in regulating crop production capacity.

This chapter will, therefore, detail some of the predominate plant abiotic stress affecting world food crops, their effects and possible coping strategies in view of promoting better agriculture and a more stable food secured nation in climate-sensitive developing countries of the tropics.

2 Stresses in Agriculture

Stress in agriculture is regarded as negative deviation from the normal physiological processes in plants. It could be directly or indirectly responsible for the disruption from ideal functions of the plant (Patakas 2012; Hartfield and Prueger 2015; Verma et al. 2015). Crops usually experience stress throughout their life cycles. In the life cycle of all crop plants, the environment tends to induce stress which could be either biotic, abiotic or both – which affects the normal growth and development of crops. The intensity of the effects imposed by these two broad categories of plant stresses cannot be endlessly debated. However, vast reports have suggested that abiotic stress poses the greatest impacts on the productivity of crop plants all over the world (Kumar 2013). Similar reports were made by Gusta (2012) in a study on abiotic stress and agricultural sustainability where abiotic stress was observed to be the predominant limiting factor (temperature, drought, salinity and radiation) for crop yields. The biotic and abiotic stresses occur at various phenologies of every crop plant. The abiotic stresses imposed on plants include (but are not necessarily limited to) extreme temperature and radiation, drought, flooding and salinity, while some of the biotic stresses affecting crops include (but are not necessarily limited to) birds, rodents, insect pests, human activities and microbial pathogens (predominantly viruses).

Owing to the increasing climatic conditions in the tropics and most temperate farming regions of the world, agricultural crops have been noted to battle the issues of increasing temperature, drought in most of the sub-Saharan regions of the tropics, cold in temperate environments and heat in most arid regions of the globe. This has simultaneously induced issues of high salinity, waterlogging in rainforest regions and extreme radiations in the sub-Saharan environments – exposing plants to severe attacks by pathogen, insect pest and disease pathogens which ultimately reduces the overall crop productivity.

Furthermore, one imperative challenging issue for most agronomist is the success in identifying and understanding with tremendous accuracy and precision the various distinct effects imposed by the two broad classes of plant stress. It is noteworthy that the first step towards salvaging the problems of plant stress is the accurate identification and understanding of the various effects imposed by either the biotic or abiotic stress factors of crops. Venkateswarlu et al. (2008) reported that although plants can encounter either biotic or abiotic stress, often times, however, a plant can be affected by more than one stress factor at any developmental stage. This is an increasing impediment to the full understanding of plant stress effects and the challenges in providing adequate coping mechanisms for them.

3 Effects of Abiotic Stress

Plant abiotic stress factors ranging from drought to extreme radiation effects on crops detrimentally alter the growth and developmental processes in crop plants at various stages of their life cycles. Most of the environmentally induced stress effects on plant are due to abiotic factors (Gusta 2012). For example, Gobin (2012) observed that stomata closing in plant leaves as induced by an abiotic factor (sunlight) tends to reduce the cooling processes associated with evaporation. Similarly, Wand et al. (2009) earlier observed a study on the responses of wild C_4 and C_3 grass species to elevated atmospheric carbon dioxide (CO_2) concentration and reported that under high CO_2 concentration, there was a marked increase in the assimilation of carbon and increased water use efficiency in plant leaves. Temperature variation is another abiotic factor that affects water absorption and fluidity of plant cell membranes. Viscosity (a resistance to the flow of a liquid) markedly and linearly decreases with decreasing temperature in crop plants. The viscosity of water in plants highly influences the relative balance of water absorption and evapotranspiration.

Rodriguez et al. (2015) added that temperature stress efficiently reduced the fresh weight of some crops. In another experiment conducted by Kaur et al. (2017) on the detection and management of abiotic stresses in a wheat field using remote sensing techniques, they reported that to combat the issues of thermal stress in agriculture, the adoption and use of appropriate planting time, foliar spray of micronutrients and salts, mulching, cover cropping, use of tree shades and adequate nutrient management techniques are highly needed. They also noted that during events of a sustained increase in air temperature and relative humidity, crop plants are exposed to heat stress. Heat stress combined with a low relative humidity condition normally results in a low dry matter production due to stomata closure in crop plants.

Gobin (2012) emphasized that crop plants faced the risk of poor nutrition due to unavailability of some or most essential and beneficial plant nutrients during periods of high relative humidity. Another abiotic stress that significantly regulates crop performance is drought. The effects of drought in the life cycle and productivity of crops cannot be overlooked. These effects are highly significant in the life of most economic crops such that they often account for the variability in the yield of cereal crops such as wheat, maize (*Zea mays*), millet (*Pennisetum glaucum*), etc. For example, Schlenkera and Roberts (2009) observed a decrease in maize and soybean (*Glycine max*) yields under water-stressed condition. Generally, drought effects have been identified with a decrease in stomatal conductance, poor vegetative growth and seedling development as well as total plant dry matter content. In Nigeria (especially the Northeast and Northwest regions), drought stress has not only influenced crop production in the areas but has also significantly affected the livelihood of rural dwellers. Crop losses due to drought stress in Nigeria coupled with her brunt population increase as accentuated by increased market demand for food crops have necessitated the imperative quest to combat drought for sustainable crop production and normal well-being of people in this region of West Africa. The intensity of the effect of drought stress on crop plants varies at each physiological and developmental phase. These effects are often more pronounced when drought occurs in synergy with heat stress. More details of the effects of each abiotic crop plant stress factor will be discussed in subsequent sections of this chapter.

4 Types of Abiotic Stress in Crops

Patakas (2012) observed that the most limiting abiotic stress factors for global agricultural production are extreme temperatures, drought, heavy metals, salinity and radiations. These stresses singly and/or in combination have been noted to pose the bulk of the impediments to crop yields in different parts of the globe. Similarly, Mantri et al. (2012) noted that temperature, water, radiation and nutrients represented the major abiotic crop stresses usually observed in crop production. For comparison, the bulk detail of the abiotic and biotic stresses mainly observed in agricultural crops was presented in Fig. 1.

4.1 Temperature Stress

Crop production all over the world is greatly influenced by temperature ranges, which limits the kind of crops that can be produced in certain regions of the world. Temperature is a very influential climatic factor that greatly affects the growth and development of virtually all species of agricultural crops in the world. The extremes of temperature have over time imposed stress on crops during the process of their life cycle. Air temperature is very pertinent to agriculture as regards its influence on plant growth through biochemical processes (nutrition, photosynthesis and respiration). Temperature and water conditions of a given region are the two most fundamental indices that farmers often consider when deciding on the choice of crop to produce, the varieties to consider as well as the level of growth, development and yield obtainable from such crop. For example, Hartfield and Prueger (2015) revealed that pollination which is the most delicate phonological stage in all agricultural

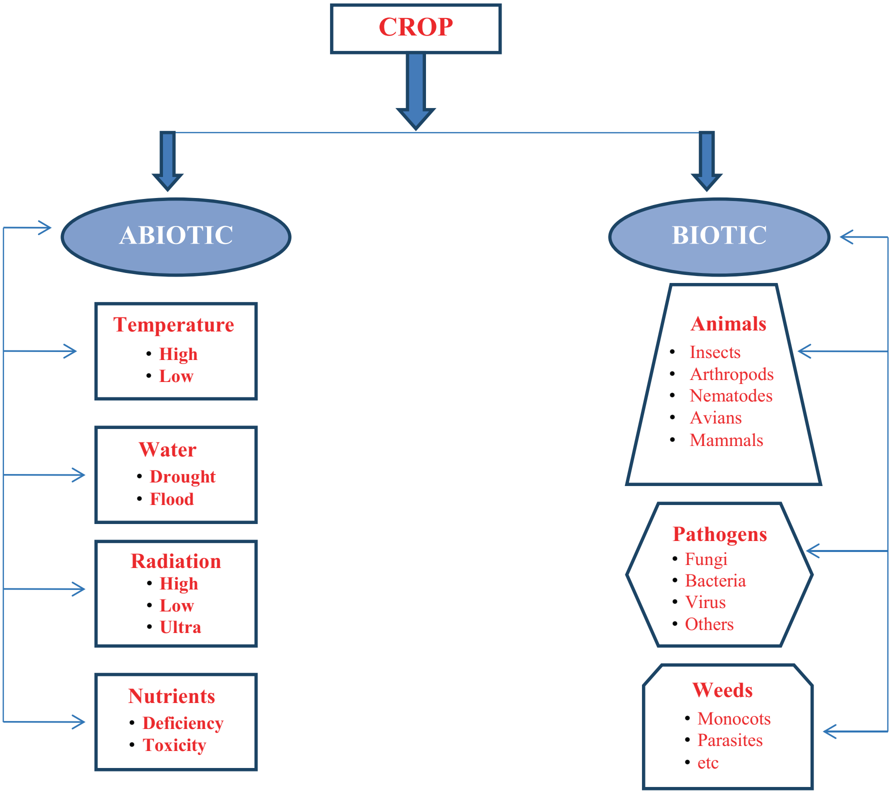

Fig. 1 Abiotic and biotic stress factors of agricultural crops. (Patakas 2012)

crops is very sensitive to temperature extremes across all kinds of crops and, as such, crop production may be greatly influenced by the extremes of temperature during the developmental phase of crops.

Similarly, Rodriguez et al. (2015) added that temperature variation is one of the predominant factors influencing plant phenology, stratification and vernalization. Crops were also found to be very sensitive to extremely low temperature. In addition, annual variations in atmospheric temperature have also been recorded to support several developmental stages in plants (germination, flowering, etc.). Owing to the assured and experienced changes in global temperature regimes, there is no denying that the effects of temperature to crop production will definitely continue to present itself as a delicate issue and threat to food security in developing countries of the tropics. Meehl et al. (2007) noted that between the two temperature extremes, the daily minimum temperature will tend to vary more drastically than daily maximum temperatures. This trend shows that an increase in the daily mean temperature could pose adverse effects on the growth and developmental processes of several food crops like wheat, maize, sorghum (*Sorghum bicolor*), etc.

Rhodes and Nadolska-Orczyk (2001) devised that extremely low temperatures could induce slow and steady freezing of plant tissues which could result in extracellular ice formation leading to the dehydration of plant cells. Temperatures have been unanimously observed to influence all species of agricultural crops that can survive in a given region. This, therefore, delineates agricultural crops into temperature classes, as these classes are the benchmarks for their optimum growth and development in unique regions best suited for the temperature range that binds each temperature class (Table 1). It is pertinent to note at this point that to effectively understand the effects of the temperature stress induced by climate variation in cropping regions of the world, it is imperative to explain some of the roles of temperature in crop growth and development. Similarly, a temperature is greatly important in seed germination of crops as the inhibition stage of the germination process for crops is extremely sensitive to low temperatures. As a result, most agricultural crops would seldom germinate at an extremely low temperature (usually below 10 °C). Also, temperature strongly coordinates the biochemical processes that succeed the inhibition phase in the germination process.

The rate of photosynthesis which is a process by which green plants manufacture their own food for better growth and development is greatly promoted by an increase in daily temperature. Studies have revealed that the photosynthetic process in agricultural crops tends to increase when the temperature rises from 5 °C to between 35 and 38 °C, as the rate of photosynthesis tends to double for every 10 °C rise in temperature. Most desert and C_4 plants (like maize) tend to thrive exceedingly well with their photosynthetic process at higher temperatures which usually range from 0 to 40 °C. Unlike C_4 plants, C_3 plants tend to react differently to high air temperature condition. The summation of the total heat units averaged during crop growth influences the physiology and developmental stages of crops.

Temperature deviations during the crop reproductive stage significantly modulate the quality and yield of seeds. Also, the seed weight, as well as the physical and chemical quality of most crop seeds, is greatly affected by the alternating short-day conditions experienced during grain or pod filling periods of crop developmental processes. The periodicity pattern of temperature observed especially in most

Table 1 Temperature classification for common food crops (Hartfield and Prueger 2015)

Temperature class	Temperature delineation	Main regions observed	Type of vegetations in the region	Common crops produced in the region
Mega – therms	Equatorial and tropical	Characterized with high temperatures all year round	Rainforest	Rice, cassava, yam, groundnut
Mega – therms	Tropical and subtropical	Characterized by constant variation in high and low temperatures	Scanty forest juxtaposed with evergreen grassland	Maize, sorghum, wheat, etc.
Micro – therms	Temperate with high altitudes	Characterized by low and high temperatures	Coniferous forest with alpine vegetation	Potato, wheat, oats, barley, orchards, etc.

leguminous crops has been revealed to be an essential factor influencing biomass production, as well as the behaviour and nodulation pattern of plant roots. Similarly, crop respiration tends to increase with increases in atmospheric temperature. This temperature increase is however bounded by critical levels beyond which respiration rates gradually decline which ultimately lead to adverse effects on crop growth and development.

Like photosynthesis, crop respiration has been reported to increase for every 10 °C rise in air temperature, provided all other factors are constant. Furthermore, a deeper look into the embryonic biology of crops, it could be observed that temperature is responsible for the abnormalities found during the boot stage in rice (*Oryza sativa*) development as the pollen grains become sterile when exposed to temperature periodicity between 35.5 °C and 23.1 °C as maximum and minimum temperatures, respectively (Kim et al. 1996). This could be attributed to the sterility of the spikelet during the meiotic process of cell development. Temperature also plays vital roles in flowering and the growth of every crop species in the world. Lower temperatures are usually required in many agricultural crops in order to initiate the flowering process. Crop pathogens, weeds and pest tend to thrive well mostly in regions with high temperatures, thereby attacking and damaging the agricultural crops and acting as major threats to food production, availability and affordability in this challenging period of climate change. In addition, the temperature is imperative to soil processes that synergistically contribute to the soil-plant-atmosphere continuum.

Atmospheric temperature influences the temperature of soils which regulates the biochemical processes like organic matter decomposition, evaporation processes, the salinity of soils, etc. At higher temperature, soil temperature tends to increase which promotes organic matter decomposition and subsequent release of soil nutrient for plants to use to complete their life cycle. Higher atmospheric temperatures induce evaporation processes thereby reducing the water table and, as a consequence, reduce the soil available water to plant roots to utilize for their metabolic processes. Soils with high saline content tend to become saltier when evaporation occurs at higher soil and atmospheric temperatures, thereby precipitating the excess salts at the soil surface which tend to serve as detrimental conditions for most food crops in the humid and sub-humid tropical regions of the world.

The roles of temperature in crop production cannot be overemphasized. As a result, the effects of temperature to agricultural crops in the face of the changing climatic conditions in the world today similarly cannot be overemphasized (Hartfield and Prueger 2015; Meehl et al. 2007; Nwosu and Okon 2012; Dhakal et al. 2016). With the assured changes in atmospheric conditions, and the forecasted increased changes in mean daily temperatures, agricultural crops are generally affected by these currently and impending variations in climates which at different points will exceedingly affect growth, development and overall yield of crops if coping and mitigation mechanism are not instituted through breeding programmes and environmental mitigations strategies for the support of health food crop production and a step towards achieving food security in the tropics. Rodriguez et al. (2015) in a study on the stress effect of temperature on the early vegetative development of cabbage (*Brassica oleracea* L). revealed that biennial crops are seasonally exposed to varying temperature from 0 to 40 °C and above, but cabbage presents itself as an outstanding plant among the biennial plant whose species are now cultivated in varying regions of the world characterized with varying climatic conditions.

4.2 Heat Stress

Heat stress in agricultural crops occurs as a result of an abrupt increase in the maximum and minimum ambient temperature over a period of 7–15 days (Sato et al. 2000; Kadir et al. 2006; Hartfield and Prueger 2015; Buragohain et al. 2017). The effects of heat stress in crops range from shedding of plant leaves, flowers and fruits to total loss of turgidity of plant cell system. Heat stress also induces or hastens maturity process in agricultural crops. The normal physiology of the plant is usually disrupted, and its cumulative effects lead to crop failure and losses. Also, the effects of heat stress imposed on agricultural crops due to increase in ambient temperatures tend to inactive beneficial plant enzymes needed for the smooth running of biochemical processes in crops, thereby reducing the efficiency of most photosynthetic processes in crop plants. Heat stress influences the maturity of kernels during the milk and dough phases as a result of the variation in duration of grain fillings. This is usually attributed to an adverse effect on photosynthesis arising due to the reduction in plant chlorophyll content and early senescence of the wheat leaf and ear which are responsible for the impairment in the grain filling and translocation processes.

Wiebbecke et al. (2012) also reported that heat stress occurring from a daytime increase in temperature conditions for agricultural crops like soybean ensures a significant decline in the seed set of the male and female sterile soybean, respectively. This was similar to the report by Singh et al. (2015) in a study on seed set response to high temperatures using different genotypes of sorghum. Hartfield and Prueger (2015) added that yield potentials of crops will be adversely affected when exposed to simultaneous heat stress during the stage of pollination of initial grain and fruit set (Dupius and Dumas 1990; Herrero and Johnson 1980). However, there is virtually no doubt that the variations in climatic conditions are hugely responsible for the changes in the temperature periodicity and patterns during each cropping season. These have tremendously disrupted the normal growth and developmental patterns of agricultural crops aimed at boosting productivity in the face of the increasing demand for food as a result of the brunt increase in world population especially in the developing nations of the tropics.

Hartfield et al. (2011) noted that owing to the projected increase in temperature for the next few decades, the yield of some major agricultural crops is expected to reduce as a result of temperature and heat stresses, respectively. Hartfield and Prueger (2015) reported crop losses due to projected continuous variation in maximum temperatures to fall within 2.5% and 10% for most agronomic species. This was in line with the reports of Lobell et al. (2011) where estimated crop losses are projected to fall between the range of 3.8% and 5.0%. Furthermore, Schlenker and

Roberts in a statistical study conducted in 2009 concluded that under conditions of low carbon emissions, estimated yield losses of some major crops like cotton, wheat and maize would fall between 36% and 40%, while the range of 63% and 70% would be the expected yield reduction during periods of high carbon emissions.

Generally, perennial crops exhibit a more complex relationship with temperature variations. For example, Hartfield and Prueger (2015) and Beppu et al. (2001) reported that the response of perennial crops to heat stress and the magnitude of the effect of temperature stresses on these crops are wholly dependent on the type of crop species considered. Warrington et al. (1999) observed a reduction in the firmness of fruit quality in apples owing to a greater than a 22 °C increase in ambient temperatures. Cole and McCloud (1985) revealed a reduction in fruit yield in citrus (*Citrus sinensis* L.) when temperatures were in excess of 30 °C. Based on the aforementioned references, it is evident that temperature and heat stresses affect both perennial and annual crops of economic importance to food security in the face of the changing climate. Hence, there is a need for a coping mechanism in order to combat and/or mitigate the problems associated with heat stress on agricultural crops.

4.3 Water Stress

Water constitutes about 80–90% of the total plant biomass. Water serves as the major transport medium for all plant metabolites and nutrients. As such, water is usually referred to as the central index for all plant physiological processes. Water is responsible for many (if not all) biochemical processes in plants, and it is an integral medium for soil fertility and nutrient availability and subsequent absorption by plant roots for optimum plant growth and development and yields (Figs. 2 and 3). The importance of water to any agricultural crop species cannot be overemphasized due to fundamental roles of water in plant crops. Owing to these functions of water in crop growth and development, the inadequacy or ultimate non-availability of water to crop is always observed to be highly detrimental to any crop production process (even for crops with minimum water requirements).

Water stress refers to the condition in which agricultural crops are seldom provided with the adequate crop water requirement in order to carry out their normal physiological processes and complete each developmental phase of their life cycle. Water stress can also be said to be a condition in the agricultural field where the groundwater table is below the root zone of crops for utilization. Water stress also occurs when the amount of water available to plant is lower than the crop's evapotranspiration demand for water. Seyed et al. (2012) emphasized that water stress usually arises due to water deficit. Drought and high salinity of agricultural soils have also been expressed in numerous studies to be responsible for water stress in agricultural crops.

Nwosu and Okon (2012) observed that water stress can also occur as a result of water excesses in agricultural fields, which impairs the normal respiration and physiological processes in crops. This condition is known as flooding or waterlogging.

Fig. 2 Maize farm devoid of water stress in Ndimoko Arondizuogu of Southeastern Nigeria

Fig. 3 Cowpea (*Vigna unguiculata*) farm in Southwestern Nigeria free from water stress

Flooding conditions are usually induced when the entire cropping field is covered with water and the water table is above the soil surface as a result of excess rainfall. Drought is the most common form of water stress in tropical agriculture. Drought refers to a period of prolonging shortage in rainfall, surface and groundwater. It is simply referred to as the period of prolonged water deficit in agricultural fields for crop production.

Seyed et al. (2012) noted that drought is a multidimensional abiotic stress of agricultural crops affecting various stages of the organization of nature. Since the inception of farming operations, drought has existed in various degrees and intensities in every stage of crop production. Many studies have highlighted the effects of drought on crops as discussed below.

4.4 Effects of Water Stress in Agricultural Crops

The inadequacy or excess of water induces several effects upon agriculture at various stages of their physiological and developmental processes, culminating in an eventual decline in crop yield. This section will seek to highlight some of the detrimental effects of drought on the life cycle of crops. Dehydration and eventual death are few of the commonest effects of drought stress on agricultural crops. This arises as plants tend to need a certain amount of water at every developmental phase to carry out their physiological activities. The inability to meet this crop water requirement, coupled with the evapotranspirational demand of the crop, ensures that the plant cells begin to lose the water conserved gradually, over time the cell shrinks and the plant loses it turgidity by dehydration and eventual death if not resuscitated with the application of water for recovery. This accounts for the bulk of the effect of drought on most food crops especially shrubs.

The dehydration and plant death effect of drought on agricultural crops was demonstrated in a screen house study on the screening of Bambara groundnut (*Vigna subterranea* L. verdc.) for drought tolerance at seedling stage. The study however detailed that the Bambara groundnut accessions were not susceptible to drought after 7 days (Fig. 4), but nevertheless, some accessions were observed to be susceptible to the dehydration and eventual plant death effect usually associated with drought stress on agricultural crops (Fig. 5).

The disparity in the susceptibility of the accessions to plant stress lays a benchmark in choosing the best accessions of the crop for commercial production in areas with minimal rainfall conditions and which at the same time will guarantee maximum production of the crop.

Drought influences water relations in plants through the decline in water content and turgor in the plant. During drought conditions, there is the closure of the stomata such that there is a reduction in plant respiration processes. Drought stress also simultaneously reduces transpiration and rates of photosynthetic carbon assimilation. Agricultural plant roots take up soil nutrient in solution form. The presence of drought conditions consequently ensures that plant roots cannot take up nutrients which are highly imperative for their growth and development. These results in a reduction in the alteration in assimilate partitioning as well as a decline of the leaf area in the plant organs. Water stresses due to drought have been reported to cause an alteration in the elasticity of the cell wall of most agricultural crops. Drought

Fig. 4 Bambara plant at 7 days after drought. (Ekanem et al. 2017)

Fig. 5 Bambara plants at 13 days after water was withheld. (Ekanem et al. 2017)

effect also covers the disruption of plant metabolic process of homoeostasis as well as the distribution of ion in the plant cells.

Water stress is responsible for the reduction in the expansion of plant cells, and depending on the magnitude and/or length of this stress, there tends to be an eventual cease in the expansion process of plant cells; as such, growth rate is drastically reduced leading to stunted growth of agricultural crops. Seyed et al. (2012) attributed this to the fact that cell enlargement in plants is more sensitive to water stress than cell division. Plant stress due to drought has been reported to be responsible for some of the changes in the quality and quantity of protein synthesis in agricultural crops as the protein synthesis declines during periods of water deficits. The expressions of genes are observed to be suppressed in plants during periods of prolonged droughts, resulting in the reduction of new protein and mRNA synthesis. The relationships between drought stress and lipid content and organization in plants have been the focal point of intense researches in the last three decades (Akinci and Losel 2012; Meena and Yadav 2014).

Lipid highly influences the physiology of protein in plant cell membrane, buttressing the fact that their significant roles in the cell membrane of plants are not in dispute. Lipid is usually affected by poor water supply, as since it has been established a major component of plant cell membrane, then there is a disruption in the normal functioning of the membrane of plant cells (Navari-Izzo et al. 1993). Drought stress also accounts for the disruption of the normal relationship between membrane lipids and proteins, beneficial enzyme activity as well as the transport capacity of membranes (Bernacchia and Furini 2004; Seyed et al. 2012). The effects imposed by drought stress on plant lipids are crop dependent. Nevertheless, Table 2 summarizes some of the main effects of drought stress on lipids in the plant. The variations in the composition of fatty acids as well as peroxidation of plant lipids have been attributed to drought stress. Like temperature stress, photosynthesis in plants is usually very sensitive to water stress. As a rule of thumb, the process and/or rate of photosynthesis decreases with the corresponding decrease in water content of plants or soil as well as the leaf water potential. For instance, in C_4 plants, water stress is arguably identified with the closure of the stomata which apparently inhibits the process of photosynthesis. Water stress also significantly impairs normal plant respiration as it tends to reduce the amount of CO_2 the plants receive due to stomatal closure. Water stress has been reported to reduce chlorophyll contents of crop plants

Table 2 Summary effect of drought stress on plant lipids

Crop type	Effect on lipids	Sources
Soybean	1. Increase in glycolipids	Akinci and Losel (2012)
	2. Increase in di- and triacylglycerol	Navari-Izzo et al. (1990)
Wheat	1. Increase in free fatty acids (FFA)	Akinci and Losel (2012)
	2. Increase in phosphatidylcholine (a phospholipid)	Quartacci et al. (1994)
	3. Decrease in glycolipids	Kameli (1990)
		Chetal et al. (1981)
Alfalfa	Blunt rise in content total lipid content	Akinci and Losel (2012)
		Al-Suhaibani (1996)
Maize	1. Decrease in content of phospholipids	Navari-Izzo et al. (1989)
	2. Decrease in FFA and polar lipids	
Cotton	1. The decrease in glycolipids and phospholipids	Wilson et al. (1987)
	2. Increase in saturation of fatty acids	Akinci and Losel (2012)
	3. The decrease in synthesis of galactolipids	Pham et al. (1982)

as well as ensures the inhibition of the chlorophyll synthesis process, respectively. There is also an accelerated reduction in the quantity of rubisco in plants during conditions of water stress. This invariably ensues the lowering of the activity of enzymes in plant metabolic and biochemical processes.

In addition, water stress poses tremendous influence on plant mineral nutrition. Studies have shown that plants growing under extreme periods of water stress tend to contain 50% less of Ca^{2+} and K^{+} when compared to plants growing in conditions where water is not limiting. The role of (Ca) in every agricultural crop cannot be overemphasized. Among the other functions of Ca reported in numerous studies, Ca is an important element in the structure and function of the cell membrane in plants. K is responsible for drought resistance as well as stomatal movements in plant crops. Seyed et al. (2012) reported reductions in nitrogen (N) uptake in crops growing under water stress conditions. Water stress has also been identified to be responsible for the disturbance in ion homoeostasis in plants as well as cell membrane damages as a result of the shrinking effects observed during periods of water deficits. Akinci and Losel (2012) reported that water stress is the predominant abiotic stress affecting most crop production in the world, especially in arid and semiarid regions of the tropic. The shortage of supply of water directly and/or indirectly affects crop growth and development. As earlier noted water stress affects not just the root growth of plants but also limits short growth at varying degrees depending on the extent of drought and the individual crop species.

Water stress which is common when soil water condition is at the *wilting point* (a condition when the plant root cannot extract water from the soil due to the very low water table and low relative humidity) causes mechanical impedance in cropping fields. Kozlowski (1968) reported that water stress in agricultural plants does not only affect plant yield but also affects the quality of the crops produced as well as the taste of fruits. Since water has been previously established as an essential irreplaceable of all crop production cycles, shortages in the supply of water even in temperate or tropical rainforest regions of the world will significantly suffer crop losses and poor yield as the changing climatic conditions progress throughout the next few decades. Gerakis et al. (1975) added that owing to water stress in crop production, there is an inverse relationship between a total nutrient and water stress for crop plant in grassland areas. The effects of water stress are a threat to food security in the developing worlds and an impediment to the growth of world agricultural production as evident in the number of crop losses and yield decline obtained due to shortages in the water supply. Understanding the measures by which agricultural crops respond to changes in water conditions as induced by the changing climatic conditions in a particular agricultural region is highly imperative in instituting modalities that curb this abiotic stress in a crop plant.

Breeding for drought-resistant varieties of crop species to battle detrimental effects imposed by climatic conditions is a necessary step towards attaining a more productive and sustainable crop production, especially in tropical Africa. Increased studies have been conducted to develop accessions of crop species that can thrive well under water (drought) stress conditions. An example is Bambara groundnut, where Ekanem et al. (2017) in a study on Bambara groundnut tolerance to seedling

Fig. 6 Bambara seedlings response to induced drought. Some surviving seedlings 17 days of withholding water were observed. (Ekanem et al. 2017)

stage drought observed that out of 100 accessions tested, accessions TVSu-750 and TVSu-553 were the most drought-tolerant at the seedling stage as they showed the least wilting under stress and also recovered from the apical meristem (Fig. 6).

4.5 Nutrient Stress

The success of every crop production is hugely dependent on the presence and availability of essential plant nutrients, without which they can seldom complete their life cycle. The importance of plant-required nutrient in the growth and development of crop species in world agriculture is not in dispute. Soil nutrient is extremely important in every growth and developmental processes in the plant. These functions are observed to be dependent on the kind of essential nutrient. Different soil nutrients play unique roles in the life cycle of every crop ranging from root development and general growth and yield of crops. In the face of the changing climatic conditions observed in today's agriculture, and with the projected changes to come, the availability of essential nutrients for crop growth in the soil has been seriously threatened as the effect of soil erosion, drought and flooding increased over time with the changes in annual rainfall, temperature and relative humidity conditions in the region.

Soil nutrient is available to plants in solution form; as such, in conditions of water deficit in cropping lands, plants are consequently limited in the amount of essential nutrient available for uptake. This entails that temperature and water stresses are the chief causes of nutrient stresses in cropping fields. Nutrient stress in crop production refers to the condition in the plant growth and developmental periods where essential nutrients required by plants are either in limited supply or in toxic levels that induce significant changes in the life cycle of the plant. Researchers have demonstrated that some plant nutrients are observed to be in limited supply during changing temperature and water conditions in the field (provided human activities are not deleterious to crop production). Alam (1999) reported that the nutrient absorption rate in plants decreases with an increase in drought stress, detailing the significance of water to nutrient availability and absorption by plant roots. It is estimated that an excess of 60% of most agricultural soils poses a limiting problem to crop production owing to mineral deficiencies and toxicities. Ensuring the right balances of essential nutrient are predisposed to crops when temperature and water are not limiting is highly imperative for any successful crop production.

4.6 Nitrogen Stress

N is a component nutrient among the primary nutrients required by plants for optimum growth and development. It is usually required in relatively large quantities and as such is normally referred to as a macronutrient in plant nutrition. N is particularly important to plants as it is a fundamental component of the chlorophyll and as such plays a vital in the formation of amino acids and proteins. Plants with an adequate supply of N are usually characterized with vigorous root and shoot growths with evergreen leaves. However, the benefits of N to plants cannot be overemphasized, but in events of N stress in plants, deficiencies will be characterized by stunted growth and yellowing of leaves (starting with the lower leaves progressively to the upper leaves). In conditions of N toxicities, the plant tends to experience prolonged vegetative growth with delayed flowering and fruiting (Hodges 2014; Ashoka et al. 2017). Furthermore, N toxicities also increase the plant's vulnerability to diseases as a result of the tender and succulent nature of their growth. N excesses have also been identified with the breakage and lodging situations in the plant, which leads to crop failure and eventual decline in crop yields. N stress in plants is a serious and sensitive situation in plant nutrition, and as such, establishing modalities to curb and ameliorate this abiotic condition in farming fields is imperative for a robust crop production returns.

4.7 Phosphorus Stress

Phosphorus (P) is a major nutrient in crop nutrition required in lesser amount compared to other major crop nutrients. P is highly responsible for energy transfer through the developmental stages of the crop. P has also been identified to be responsible for the early fruiting and root developments in younger plants and as such plays vital roles in the early developmental phase of most plants. P is a major component of plant seeds and tends to influence seed formation. P stress in conditions of inadequacies ranges from poor root development in younger plants, the decline in vegetative growth leading to stunted growth conditions, poor quality of seeds (for seed plants) and a general decline in crop yield. Like N, excesses of P are normally characterized with prolonged vegetative growth and early ripening of immature fruits.

4.8 Potassium, Magnesium and Calcium Stress

Potassium (K) completes the group of primary nutrients in plant nutrition. It is very important in plant respiration during the photosynthesis process, as it is responsible for the opening and closing of the stomata. K is an enzyme activator and plays crucial roles in the formation of adenosine triphosphate – a vital energy for most plant biochemical reactions. K is also important in starch and protein synthesis through its action in activating enzymes that speeds up or slows the chemical process.

The transport of water and nutrients throughout the xylem of plants is influenced by K. The importance of K to crop plants is endless as more studies are trying to establish more complex roles of K in the life cycle of crops. When crops undergo K deficiencies, the symptoms are evident in chlorosis of leaves. In addition, visual symptoms will include stunted growth, impaired respiration and water movement in plants. Toxicities in K concentration usually lead to antagonistic effects on other nutrients like Ca (calcium), Mg (magnesium) and N (nitrogen). About 20% of plant Mg is present in the chlorophyll. Mg is also an important enzyme activator and plays crucial functions in P reactions and synthesis of plant proteins. Mg deficiencies in plants result in interveinal chlorosis and reduced vegetative growth. Excess concentration of Mg results in increased vulnerability of the plants to diseases and poor synthesis of proteins. As a structural component in the cell wall of plants, Ca is an established major component of plant leaves.

Ca is important in the growth process of plant cells, and it influences nitrate-N uptake in the plant. Stress associated with deficiencies in Ca in plant exhibits poor root development and poor quality of fruits produced. Toxicities in Ca are usually associated with impaired root development and prolonged vegetative growth in plants. Nutrient stresses in agricultural crops are usually manifested when the environmental conditions of the crop are seldom favourable for the optimum growth and development of crops. Hence, baring the human activities that influence poor soil nutrient qualities, water and temperature conditions of the field are responsible for the bulk of the induced nutrient stress in agricultural crops. This lays credence for the increasing need to ensure an adequate supply of water and fertilizer (organic and inorganic) in the right balance for the optimum growth of crops especially in the face of the projected changes in climatic conditions.

4.9 Radiation Stress

Radiation of varying wavelengths and intensities usually subjects plants to varying degrees of abiotic stress. Ultraviolet (UV) radiation is one of the most harmful abiotic stress factors of radiation. This is in many parts attributed to its association with biologically absorbing UV molecules such as nucleic acids (NA), lipids and proteins, as well as their detrimental effects on plants. The effect of UV radiation on agricultural crops largely depends on the wavelength, length of crop exposure to radiation, irradiance and the genetical constitution of the plant species exposed to UV radiations (Cramar et al. 2011; Yadav et al. 2017).

Teveni (2004) added the morphological and protective features of the plant as other important factors modulating the degree of crop effect induced by UV radiations. Studies have shown that the shorter the wavelength of the UV radiation, the higher the injurious impact on crops. With projected changes in climatic conditions, coupled with the accelerated depletion of the ozone layer, UV radiation remains an important threat to food security in view of its effects on crop production. UV-C radiation (nonsolar radiation) with a wavelength of about 281 nm remains the most harmful UV radiation with the greatest threat to food production. The effect of UV-beta radiation (from solar radiation) with a wavelength range of 290–320 nm increases with the increase in ozone layer depletion by halogenated gases such as chlorofluorocarbons. The effects of UV-beta radiations which are more pronounced in photosynthetic plants range from destruction of DNA, plant proteins and lipids to disturbance and eventual damage of the plant cell membrane. Prolonged impact of UV radiations culminates in loss of plant turgidity and eventual death of plants in extreme cases especially in arid regions of the tropics. Efforts have been established to ascertain more effects of radiation on crop production; however, there is increasing need to establish coping means to combat these deleterious effects in the face of the changing climatic condition and food security challenges especially in tropical nations.

4.10 Plant Responses to Abiotic Stress

Several researchers have documented that the response pattern to abiotic stress is a function of the individual plants considered. However, this section will focus briefly on some of the general molecular responses of plants to environmental stress based on biology system of plants. Cramer et al. (2011) in a review on the effects of abiotic stress on plants revealed that there is an increased effort in understanding the complex molecular control process fundamentally via three systematic methods identified with the adaptation and tolerance of plant abiotic stress. These methods include:

- *Transcriptomics* which involves the analysis and expression profiles of coding and non-coding RNAs.
- *Metabolomics* which is a very effective tool for metabolite analysis in large quantities.
- *Proteomics* which gives more insight into understanding the network regulatory processes in protein and their modification profiles.

The establishment of the three aforelisted systemic analysis progressively facilitates researches involving signaling for abiotic stress in plant species and invariably supporting for more comprehensive identifications of molecular target identifications and future use of biotechnology in agricultural plants (Cramer et al. 2011). There are many molecular pathways and interactions associated with agricultural plants' responses to environmental stress. Mittler et al. (2011) reviewed the use of reactive oxygen species (ROS) signaling and its interaction with plant hormones for abiotic stress response in crop species. Together with the reactive N species, ROS tend to coordinate several abiotic stress responses in plants. Furthermore, studies by Goda et al. (2008) have observed that ABA and ethylene make up the bulk of the plant hormones that regulate abiotic stress in plants. ABA is a very important osmotic stress regulator in plant, and the dehydration and salinity stress in plants are also thought to be dependent on ABA. Cramer et al. (2011) and Yamaguchi-Shinozaki and Shinozaki (2006) noted that when plants are subjected to abiotic stress owing to dehydration, there is an associated increase in the endogenous ABA levels. Ethylene, on the other hand, has been identified in many abiotic stress responses involving moisture, heat and radiation, respectively (Cramer et al. 2011; Wilkinson and Davies 2009; Goda et al. 2008; Morgan and Drew 1997). Ethylene interactions with ABA in plant responses to abiotic stress have been documented in fruit ripening and dormancy of plant buds (Sun et al. 2010; Cramer et al. 2011; Meena et al. 2017).

However, Wilkinson and Davies (2009) added that, due to the interaction between ethylene with ABA, the plant response signaling process to environmental stress have increasingly become a more complex study (Fig. 7). Hence, more researches in establishing a detailed understanding of more molecular plant abiotic stress regulatory processes are needed in order to establish a more comprehensive knowledge

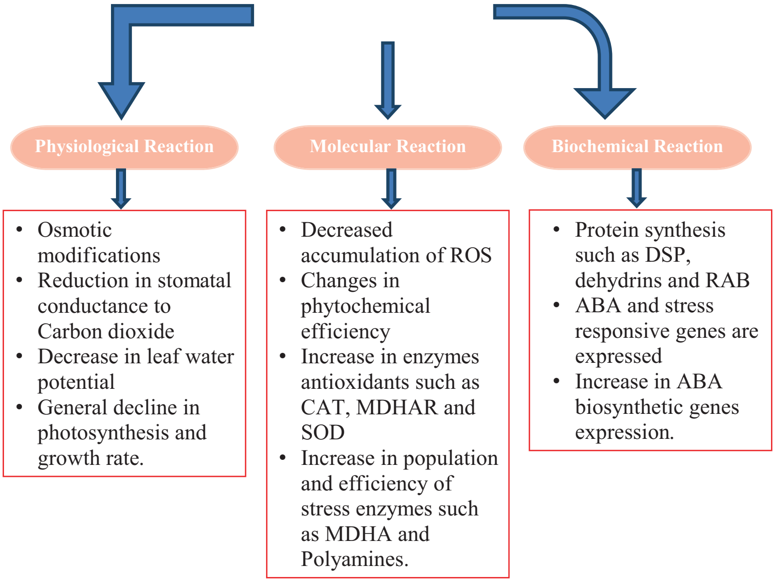

Fig. 7 Reactions to drought stress tolerance in tropical plants. (Modified: Seyed et al. 2012)

and understanding of plant abiotic stress issues in agricultural plants, of which will be extremely important in developing adaptation means in the face of the changing climatic conditions in a world agriculture.

5 Combating Strategies Towards Abiotic Stresses

The previous sections of this chapter had established that plant stress (a physiological state that is induced by factors that influences and/or alters the metabolic balance of plants at any growth and developmental stage) whether biotic or abiotic occurs during conditions of environmental imbalance due to plant high sensitivity to environmental factors of temperature, rainfall, relative humidity, wind, solar radiation, etc. While biotic stresses have been observed to predominantly manifest themselves through disease pathogens, abiotic stresses tend to profligate through all facets of plant metabolic processes. Nevertheless, both stress factors have been reported to yield significant decline in crop production through crop losses and yield of plants in each production cycle. Some of the effects of plant abiotic stress factors have been discussed in the previous section of this chapter. The pertinent task for most agronomists is devising coping mechanisms for the proper management of the abiotic stress factors in a crop plant. This section will, therefore, attempt to highlight some of the management strategies for plant abiotic stresses.

Plants respond rapidly to changes in temperature conditions at all levels of the plant system. The sensitivity of plant cells to variations in temperature is intrinsically essential during the photosynthetic study. Sirari et al. (2016) reported that plants tend to respond to extremely high-temperature conditions by producing proteins that are immune to temperature stress as well as generating metabolites (both primary and secondary) which aids in acclimation of photosynthetic processes. Simultaneously with temperature stress mitigation, plants also exhibit several processes to combat heat stress which are often than not associated with variations in maximum temperature conditions. In order to manage conditions of heat stress, plants tend to regulate the strength of their cell membranes with the aim to preserve them during extreme maximum temperature conditions. Also, productions of enzymatic and non-enzymatic antioxidants are expediently discharged by plants as a pertinent coping strategy for heat stress conditions.

Wahid et al. (2012) devised adopting conventional and molecular breeding techniques and/or principles as well as the exogenic application of the use of the osmoprotectants and other stress-dictating agents in order to adequately monitor and combat heat stress in plants. Also, stress associated with a nutrient imbalance in plants can be ameliorated by raising the soil pH to optimum levels where most essential and beneficial plant nutrients would be available for uptake by plant roots. During conditions of low pH detailing that the soil is moderately to highly acidic, lime can be added in order to raise the soil pH and enable essential nutrients like Ca, Mg, Na, K and P to be available for uptake by the roots of plants and enable the plants to combat the abiotic stress effects associated with nutritional disorder which most often leads to decreased plant growth and crop yield in addition to poor crop quality. For salinity stress management in agriculture, the application of gypsum has proven effective in reducing the saline content of most tropical soils and ensures the availability of some essential plant nutrients that are inactive under saline conditions. Issues of salinity have been widely recognized as one major impediment to sustainable food production and security in the tropics. Salinity not only induces nutrient imbalances and toxicities but also impairs normal photosynthetic processes in a crop plant. Breeding for salinity tolerance is highly imperative in any significant effort to combat salinity stress effects in tropical crops. Karan and Subudhi (2012) reported that quicker breeding methods can be adopted for identifying potential parents in breeding programmes associated with salinity management. Also, the use of plant tissue culture techniques has been reported to be another feasible approach to establishing salt-tolerant crops in the tropics. Techniques such as in vitro mutagenesis have been employed to develop variation to salt tolerance in crops. In addition, genome mapping techniques which tend to hasten the identification of the precise position and physiology of distinct genes which influences agronomic traits have gained increasing attention in molecular studies for salinity management in the tropics.

Drought stress management can be established through the production and use of resistant plant genotypes and complimented with improved and modified agronomic practices such as time of sowing, plant population density, weeding operations, irrigation and soil management techniques. Also, owing to the numerous losses experienced by most plants due to drought stress, there is an ever-increasing need and incentives by plant breeders in order to reduce the effects of drought on plant productivity – which accounts for the bulk of the plant abiotic stress effects in agriculture. Nevertheless, to manage drought stress, plants tend to produce smaller and/or shorter leaves in order to reduce water losses due to transpiration (Sirari et al. 2016). In addition, there is an improved effort by some plant roots to take up water from the soil. This is particularly enhanced through root elongation deeper into the soil profile in order to come in contact with water bodies that have been exiled further down the soil depth as a result of a sustained decrease in rainfall amounts and intensity. In addition, mulching, irrigation and foliar sprays with seed treatments are some of the other drought management techniques that have efficiently assisted in combating the issues of drought in Nigerian agriculture. Sirari et al. (2016) have also documented the importance of microorganisms in combating environmentally induced abiotic stress in crop plants. Table 3 however summarized some of the abiotic stress mitigation mechanisms adopted by some microorganisms for abiotic stress control in selected crops in the tropics.

The importance of the plant growth hormones in abiotic stress management has been increasingly undervalued in agronomic studies in most parts of the tropics. Plant growth hormones like cytokinins, auxins and gibberellins have been reported to play vital roles in plant responses to drought stress conditions. ABA has also been documented to significantly influence the response of plants to drought stress (Sirari et al. 2016; Dadhich et al. 2015).

Table 3 Abiotic stress management strategies adopted by microorganisms in crops

Type of crop	Type of stress	Mitigating organism	Mode of mitigation	Source
Wheat	Drought	*Azospirillum* sp.	Increase water content and uptake	Sirari et al. (2016)
	High salt content	*P. insolitus*	Decrease in influx of Na	Ashraf et al. (2004)
		Microbacterium sp.	The decrease in an influx of Na	Ashraf et al. (2004)
		P. syringae	Decrease in influx of Na	Sirari et al. (2016)
Tomato	Salinity	*Achromobacter piechaudii*	ACC (1-aminocyclopropane-1-carboxylate) deaminase synthesis	Sirari et al. (2016)
	Drought	*Achromobacter piechaudii*	Synthesis of ACC deaminase	Sirari et al. (2016)
	Micronutrient toxicity	*Burkholderia* sp.	Reduction in translocation and uptake	Madhaiyan et al. (2007)
Pea	High salt content	*Pseudomonas fluorescens*	ACC deaminase synthesis	Saravanakumar and Samiyappan (2007)
	Drought	*Pseudomonas* sp.	Reduction in the production of ethylene	Arshad et al. (2008) and Sirari et al. (2016)
Maize	Nutrient deficiency	*Bacillus polymyxa*	Increase in uptake of essential nutrients	Sirari et al. (2016)
		Pseudomonas alcaligenes	Increase in nutrient uptake	Egamberdiyeva (2007)
		Mycobacterium phlei	The increment in the uptake of plant nutrients	Sirari et al. (2016)

6 Research and Development in Agriculture Under Stress Condition

The advent of stress in agriculture has given rise to the institution of research programmes geared towards establishing modalities that counter the effects imposed by abiotic and biotic stress in crop production. This was considered a necessity if food production is to be sustained in the face of the changing climatic conditions and increasing population pressure on food production. Bangladesh, a country with the dense population and a high food demand, has established some research and development programmes in the wake of the stress conditions in agriculture. This was markedly observed in their development of inbred crop varieties possessing relevant features of agronomic importance. Also, agronomic traits are carried out on the evaluation of germplasm in order to identify potent lines with unique agronomic traits to be hybridized for the development of new crop varieties.

Furthermore, in Nigeria, the International Institute of Tropical Agriculture has embarked on research programmes aimed at developing improved varieties of Bambara groundnut and cowpea to resist the detrimental influence of stress effects on their normal physiological processes and yield. Bambara groundnut accessions with agronomic traits that are drought tolerant and with low cooking time have been identified and are currently being subjected to further evaluation under field conditions. This will, however, aid in increasing legume production in Nigeria and as such meet the rising demand of the produce by consumers and industries. In addition, in Nairobi, Kenya, the Biosciences for East and Central Africa have engaged in agricultural research development projects to militate against stress conditions imposed by biotic and abiotic factors through instituting breeding programmes that appreciates genomic tools and vastly sophisticated platforms of bioinformatics in order to identify and project suitable markers in crops that can resist stress effects. This is also similar to the molecular breeding programmes engaged by the International Crop Research Institute for Semi-Arid Tropics. Other research programmes have been established in the USA and Europe to battle issues of stress in agriculture – and these researches will continue to evolve due to the changing climatic conditions that will invariably impose varying degrees and kinds of stress in agriculture (Palmer 2005).

7 Sustainable Approaches Towards Combating Climatic Stress on Agriculture

Organic agriculture is one major way of combating climatic stress in agriculture. Organic agriculture tends to increase the soil's potency in mitigating against climate change effects. Niles (2008) reported that organic agriculture, more than any other production system, has the greatest potential for combating climate change. For sustainable management of climatic stress, the use of organic agricultural systems is highly encouraged in order to sustain food production and reduce environmental pollution for future cropping seasons. Seyed et al. (2012) also reported that the use of better agronomic practices like improving upon the sowing time, weeding method and irrigation strategies as well as fertilization is highly essential in order to combat drought stress and nutrient stress effects on crop plants. Weeds also compete with crops for nutrient, water, light and space – all of which are limiting during periods of climate stress; hence, ensuring a weed-free agricultural field is imperative in order to reduce the stress effects on crop plants (Karan and Subudhi 2012). This approach has been increasingly ignored in the tropics but one which presents the most sustainable approaches for managing climatic stress especially for smallholder farmers with little income earnings.

Understanding the climatic conditions and future projections is important in deciding on the planting time for crops for optimum productivity. This will enable the crops to avoid the periods that are associated with limiting water, light and nutrient conditions as well as the period of increased pest and disease infestation which is characteristically aided with warmer climatic conditions. This approach is considered cheap and sustainable for smallholder farmers, especially in the semiarid and humid tropics. More so, conserving the soil which is the hub of most farming operations is highly essential for sustainable crop production and mitigating of all forms of climatic stress. The soil tends to accommodate various degrees and intensities of rainfall, solar radiation and humidity and channel these climatic factors into productive biological processes for plant benefit. The excess of these factors, however, tends to impair and reduce the activities and population of beneficial soil microbes and nutrient in the soil. As such, employing soil conservation strategies and/or techniques geared towards maintaining and improving the quality of soil resources for current and future agricultural operations are highly imperative for a sustainable mitigation of environmental stress effects. Soil conservation techniques like mulching, cover cropping, use of vetiver grass strips and/or mulch, manuring and up-and-down ridging are essential for conserving soil resources in the face of climate stress conditions (Nwosu and Okon 2012; Kumar et al. 2017).

Current technologies have seen the establishment of breeding programmes that prepare the crop genetically to withstand climate stress effects. These programmes are often sustainable as they ensure that the crop varieties produced can fully express themselves to their full potentials even in the face of disturbances and climate variability inducing stress of all kinds. The use of QTL (quantitative trait loci) markers, genomic programmes, molecular programmes, etc. that aim at improving the desired trait of crop variety for current and future use is another sustainable effort to combating climatic stress.

8 Conclusions

This chapter discussed the four principal factors causing abiotic stress in agricultural crops under varying climatic conditions. Abiotic stresses caused by temperature, radiation, water and nutrients pose a great threat to food security especially in developing arid and semiarid regions of the tropics. In terms of economic importance to crop production, water and temperature stresses have accounted for highest crop failure and yield decline in the tropics. Owing to the numerous effects of abiotic stress coupled with unfavourable projected changes in future climatic conditions, there is a need to establish adaptation strategies for abiotic stress tolerance in agriculture in order to sustain crop production all year round irrespective of variability in weather conditions. With the increased population pressure on land juxtaposed with the increasing demand for food especially in tropical regions of Africa and Asia, researches involving environmental stress in agricultural crops should be given attention in the quest to sustain future crop yield expectations.

9 Future Prospective

Crop stress induced by abiotic factors of the environment has greatly altered crop production output, especially in the tropics. Detailed management strategies previously outlined in some sections of this chapter have established the increasing efforts to combat the issues of abiotic stress in a crop plant. However, with the projected climatic changes juxtaposed with the rising world population especially in the tropical regions of the globe, more effects of abiotic stress will be observed if appropriate coping mechanisms are not laid down to checkmate this obnoxious issue. The advent of molecular breeding programmes has enabled farmers and agronomists to mitigate against abiotic stress effects on food security. Nevertheless, it is projected that more increased breeding programmes coupled with new agronomic practices that provide resistance against most prevalent abiotic stress factors be employed and improved upon. The use of genome mapping techniques, QTL markers, resistant genotypes and practices that enable the crop to express their physiology for better growth and development should be encouraged in the face of the brunt of the population increases and rising changes in environmental conditions for sustainable crop production in tropical regions.

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Agroforestry: A Holistic Approach for Agricultural Sustainability

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Abstract

Agroforestry is gaining a higher position and becoming a specialized science with integration of both crops and forestry science. The sustainable land use farming practices are involved in various life forms of plants/trees with livestock on a single piece of land creating more diversification with multiple outputs, enhance biomass productivity, reduce atmospheric carbon dioxide (CO_2) through absorption and fixation and protect the environment through ecosystem services. In modern day, the adoption of agroforestry is continuously rising due to their biophysical, socio-economical, cultural and environmental services in the tropical condition. In the era of climate change, it gives diversifying food and fruits under different type of agroforestry models (AFM) and can solve the food and nutritional problem of the people in society. From the Indian perspective, agroforestry is being practiced about 14 Mha, but if explored properly it has further higher potential to increase the land area under agroforestry. It was found that up to 65.0% of timber and 50.0% of fuelwood come from the agroforestry sector. Therefore, agroforestry has also the potentiality to reduce poverty, increase income generation and provide alternate economic sources. Along with other benefits, the practices of agroforestry are economically viable for the farmers which generate employment. Various choices for farmers are available for adopting different types of AFM integrating numbers of the tree crop with livestock in various agroclimatic zones. Farmers have an option to select AFM as per socio-physical conditions (i.e. land holding, economic condition, climatic condition, resource availability, market economy). Apiculture- and sericulture-based agroforestry is another option for farmers for alleviating poverty and enhancing socio-economic conditions. From the ecological point of view, agroforestry may potentially maintain the soil quality and health which is linked with the fertility of soil and decomposition of soil organic matter. Thus, there is a nexus between soil fertility and crop productivity in various agroforestry systems (AFS). From a research point of view, there is a need for conservation of superior germplasm of agroforestry components along with their proper domestication and utilization. This chapter deals with interrelationship between soil health, productivity under AFS addressing natural resource conservation, food security and livelihood security towards sustainability. Research should be undertaken for maximizing the productivity of trees and crops under agroforestry for continuous benefits to farmers along with environmental protection and ecological security and sustainability.

Keywords
Agroforestry · Ecological security · Productivity · Soil fertility · Sustainability

Abbreviations

AFS	Agroforestry system
AFM	Agroforestry models
C	Carbon
CO_2	Carbon dioxide
GHGs	Greenhouse gases

1 Introduction

Agroforestry has its origin since ancient times as an age-old practice over earth surface. In such a system, cultivation practice was done under economically important plant species. Such an integrated approach serves the dual purpose of crop cultivation and off-farm output. The inclusion of a tree in the agroecosystem serves the function of protection to soil health and improves the soil nutrient status. Under changing climate throughout the world, agricultural productivity is declining. As a consequence, farming community is suffering from huge economic crisis. Therefore, agroforestry is a suitable solution for them to mitigate climate change consequences as well as keep pace with the growing population. It is totally an eco-friendly approach having multifaceted benefits (Verchot et al. 2007; Jhariya et al. 2015; Raj et al. 2018a; Meena et al. 2015b).

Today changing climate is imposing high vulnerability under the extreme conditions of the climatic elements such as severe rainfall, frequent occurrence of flood, fire, drought, cyclones, etc. resulting in loss of life and money. As we know, both natural and human (anthropogenic) factors are the cause of climate change and producing greenhouse gases (GHGs) which result in warmer climate affecting the earth's system and biodiversity (Raj et al. 2018b). The effect of extreme weather is not limited and confined to traditional agricultural system, and it can also affect the complex type of farming practice like agroforestry in terms of detrimental effects on productivity, profitability and sustainability through loss of biodiversity and ecosystem services. Agroforestry is regarded as a boon in the form of coping up with climate change by its nature of complexity, diversifying yield capacity, enhancement of overall biomass productivity, improved food and nutritional security and soil amelioration capacity through various ecosystem services along with environmental resilience capacity (Verchot et al. 2007; Jhariya et al. 2015; Raj and Jhariya 2017; Verma et al. 2015). As we know, agroforestry is site-based farming systems, which prevailed in the tropics of the world, and consists of three elements (tree, crop and livestock/pasture). It appears in the form of various models, namely, agrisilvicultural, silvipastoral and agrisilvopastoral, as per the combination of these three components. Systems of agroforestry can be implemented anywhere such as in field boundary, bunds and wasteland areas. It maintains overall biodiversity and plays a significant role in soil conservation, carbon dioxide (CO_2) absorption through carbon (C) sequestration, enhancement of overall biomass productivity and employment generation along with poverty eradication of farmers. Also, the complexity of agroforestry system (AFS) gives a more diverse form of produce along with environmental protection through intangible/indirect benefits like soil water conservation, watershed management, efficient nutrient cycling and better ecosystem sustainability. It is very well known that agroforestry produces more than one output as tangible/direct benefits in the form of timber, fruits, food, fuelwoods, etc. which may promote upliftment in socio-economic status of poor farmers.

Agroforestry practice varies depending upon various climatic zones, biogeography as well as environmental factors. Besides these factors, land holding, adoption by the farmers, funding supports from governmental and non-governmental organization and nation policies also influence the extent of agroforestry across the world. As per the FAO report, the total area of agroforestry system in the world is 1023 million hectare (FAO 2000). Globally, 307 mha area is under agroforestry practice out of 823 mha area (both agroforestry and silvopastoral system) (Nair and Garrity 2012). Similarly, South America covers maximum areas of agroforestry (3.2 million km^2) followed by sub-Saharan Africa (1.9 million km^2) (Kumar et al. 2014). The area of agroforestry in India has been increasing from 7.4 mha in 2007 (Zomer et al. 2007) to 25.32 mha in 2013 (Dhyani et al. 2013). From Indian perspective, agroforestry is being practiced in a large area, but if explored properly it has further higher potential to increase the land area under agroforestry. It was found that up to 65.0% of timber and 50.0% fuelwood comes from the agroforestry sector.

The agroforestry model (AFM) is a unique one and based upon the structural and functional complexity and gives more diversification and multifarious benefits in terms of production of multiple outputs along with protection of the environment through better ecosystem services. Ecological services may vary as per different traditional and developed models of agroforestry in the given site because agroforestry is the site-specific farming system. Along with the provision of ecosystem services, agroforestry maintain diversification in productivity which enhance production and improved quality of food under changing climate (Verchot et al. 2007). In due course of time, diversification in agroforestry produce can increase through successional changes in each and every stage of agroforestry development (Leakey and Simons 1996).

This chapter is focused on the study of prevalent AFM in the tropics and the provision of ecosystem services along with a potential role in climate mitigation. This chapter also throws a light on nexus among soil health and productivity under AFS along with the linking concept between them. Natural resource conservation, food security and livelihood security are another paradigm of AFS and sustainability.

2 Agroforestry in the Tropics

It is well known that tropical region has a wide array of AFS with greater promises of adoption as compared to other climatic region. Agroforestry is not a recent practice; it is an age-old sustainable farming system comprising both trees and agricultural crops and their cultivation practices from the beginning of domestication of plant and animals. Ever since today several models of agroforestry have been initialized in both developed (Europe and America) and developing countries (Asia and Africa) (King 1987).

The model of agroforestry varies from arid to humid tropics comprising different combinations of tree, crops and livestock as per availability of resources, soil characteristics and prevailing climate (Fig. 1). Also, there are many models of agroforestry which can vary as per their functions (protection and productions), roles and outputs (multiple). Similarly, the ecological adoption of different models of agroforestry in the tropics depends on the prevailing climate of that region. For example, alley cropping is suitable for humid tropics due to ample of sunlight and moisture rather than other tropics (arid and semiarid). The presence of moisture and light is helpful for decomposition of mulches which is the basic feature of alley cropping.

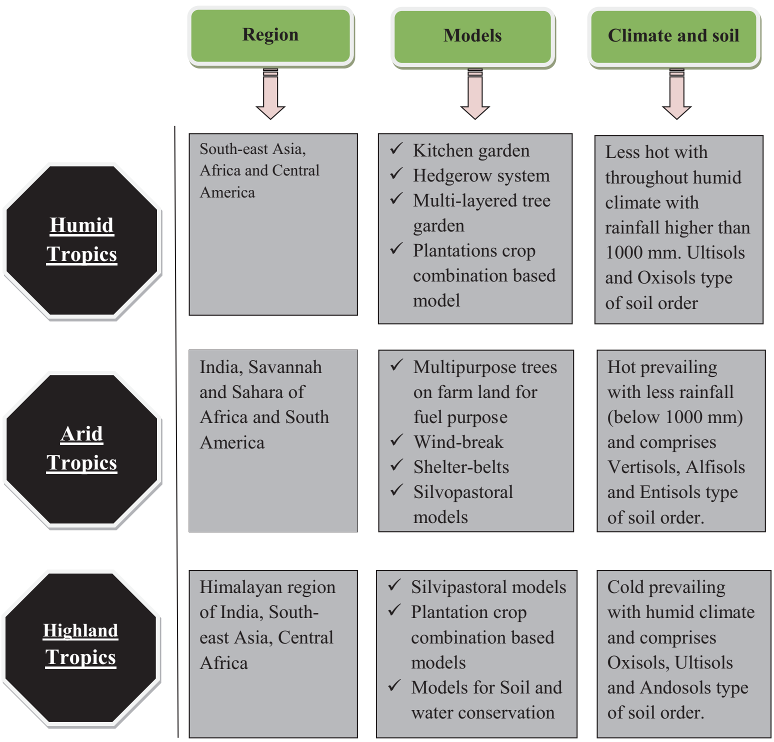

Fig. 1 AFS in the tropics. (Atangana et al. 2014a; Mercer 2004)

The various forms of agroforestry practices under tropics and various regions across the world are depicted in Tables 1 and 2.

2.1 AFS in Arid Tropics

Arid tropics are characterized by higher temperature with less rainfall (below 1000 mm) and comprised of vertisols, alfisols and entisols soil orders. India, Savannah and Sahara of Africa and South America are the major geographical distributions of arid tropics. Multipurpose trees on farmland for fuel purpose,

Table 1 AFM in major tropics (Nair 1993; Sinclair 1999; Mercer 2004; Atangana et al. 2014a)

Tropics	Models	Components
Arid/ semiarid	Agrihorticulture system	Agricultural crops + fruit trees
	Agrihortisilviculture system	Agricultural crops + fruit trees+ trees other than fruits
	Hortipasture	Fruit trees + pasture for livestock feeding
	Horti-silvipastoral system/ silvihortipastoral/ Agri-hortipastoral systems	Combination of horticultural trees, trees other than fruits, agricultural crops and pastures
	Agrosilvopastoral	Introduction of livestock in tree-crop systems
	Windbreak	Row of tree such as *Eucalyptus* species, neem (*Azadirachta indica*), *Dalbergia sissoo* (shisham), *Casuarina equisetifolia* (beach oak), etc. around the crop field works as a windbreak
	Alley cropping	Wide spacing tree planting along friendly crops grown in alley among rows. Subabool (*Leucaena leucocephala*) is a suitable tree because of its N_2-fixing property and its multipurpose nature
	Protein bank (cut and carry systems)	It is a type of silvopastoral systems having various protein-rich multipurpose trees like babool (*Acacia nilotica*), neem, black siris (*Albizia lebbeck*), etc. which are in and around farmlands and rangelands
	Parkland system	Trees such as khejri (*Prosopis cineraria*) in Rajasthan and apple-ring acacia (*Faidherbia albida*) in East Africa are dominant in crop fields. Prevalent in sub-Saharan Africa
Humid	Home gardens/kitchen garden	Most prevalent in high rainfall areas having combination of various multistory annual and perennial crops along with livestocks around the home
	Plantation tree-crop combination	Combination of some plantation crops like coffee (*Coffea arabica*), cocoa (*Theobroma cacao*), rubber (*Hevea brasiliensis*), oil palm (*Elaeis guineensis*), coconut (*Cocos nucifera*), spice and fruits crops, etc. with shade-loving crops
	Multilayered tree garden	Characterized by multispecies of multipurpose in nature with no organized planting arrangements

Table 2 Agroforestry areas in different regions of the world

Agroforestry systems	Area cover in million ha	References
Agrisilviculture (dominant) system in China	45	Huang et al. (1997)
National cover in India	25.32	Dhyani et al. (2013)
Silvopastoral system in Central America	9.2	Beer et al. (2000)
Dehasa agroforestry in Spain/Portugal	6.0	Gaspar et al. (2007)
All multi-strata and jungle rubber agroforestry	6.3	Van Noordwijk and Ong (1999) and Wibava et al. (2006)
Coffee agroforestry in Central America	0.77	Beer et al. (2000)

windbreak, shelter belts, silvopastoral models, etc. are the major AFS that are practiced in this region.

2.1.1 Agrihorticulture System

Integration of herbaceous field crops with fruit-bearing trees is a common practice in the arid region and can enhance the productivity of land and may be profitable to farmers in various ways. Tree-crop interactions and their competitiveness, complexity and compatibility are the major factors that decide whether the selected models are suitable for the given soil and regions or not (Krishnamurthy 1959; Naik 1963; Toppo et al. 2016). According to them, several agricultural produce such as wheat (*Triticum aestivum*), sugarcane (*Saccharum officinarum*), cotton (*Gossypium* spp.), maize (*Zea mays*), etc. are not compatible with horticultural tree species except the combination of jujube (*Ziziphus jujuba*) with other agricultural crops like green gram (*Vigna radiata*), sesame (*Sesamum indicum*) and guar (*Cyamopsis tetragonoloba*) where fruit yield increased from 5.2 to 14.8 kg per tree along with a higher yield (782 kg seeds) of guar (Singh 1997). Similarly, major horticultural crops like Indian mesquite (*Prosopis spicigera*), harbour guar and cucurbits are most suitable with moth bean (*Vigna aconitifolia*), guar, sesame and pearl millet (*Pennisetum glaucum*) under rainfed condition but suitable with chickpea (*Cicer arietinum*), groundnut (*Arachis hypogaea*), green gram and spices crops under irrigated conditions (Bhandari et al. 2014; Kumar et al. 2018).

2.1.2 Agrihortisilviculture System

High wind blow and intense sunlight are the major characteristics in arid regions. In this case integration of some woody perennial trees with any prevailing model is helpful for checking high wind speed along with soil erosion. These practices will be helpful for maintaining soil productivity and health status of both crops and trees along with amelioration of very harsh environment. Thus, integrating trees in that region works as shelter belts and windbreaks in and around the agricultural farm. Therefore, this practice will be more diverse, socially acceptable and economically sound to farmers by providing several timbers, fuel, fibre, fruits and medicinally important plants.

2.1.3 Hortipasture

Integration of some edible/nonedible grasses such as pasture for livestock with recommended horticultural crops is another type of AFS that prevails in the arid region. This system can enhance livestock's economy and profitability for farmers. Integration of some horticultural trees such citrus (*Citrus* spp.), guava (*Psidium guajava*), pomegranate (*Punica granatum*), aonla (*Phyllanthus emblica*), mango (*Mangifera indica*), etc. with some edible grasses/pasture is the major characteristic for the establishment of this model in which ground pasture can be fed by livestock and cattle. Therefore, we can say the health of livestock depends on the type and palatability of fodder and pasture species. This system can maintain food and nutritional security for both people and cattle/livestock (Atangana et al. 2014a). Furthermore, fruit tree like ber (*Ziziphus mauritiana*) in drought region can perform a better substitute in the case of any crop failure condition with the provision of nutritious fruits, fuelwood, fodder, etc.

2.1.4 Horti-Silvopastoral System

The integration of horticultural crops with trees and pasture is advantageous for arid region. This integration can check soil erosion and improve productivity and fertility of soil through continuous addition of organic matter. Therefore, the suitable combination of different elements (horticultural crops, trees and pasture) could potentially ameliorate microclimate of the arid region along with enhancement of nutritive quality and palatable characteristics of pastures and grass species on which livestock depends. Thus, several species like Kardhai (*Anogeissus pendula*), gum arabic tree (*Acacia senegal*), axlewood (*Anogeissus rotundifolia*), umbrella thorn acacia (*Acacia tortilis*), black siris, neem, phog (*Calligonum polygonoides*), phalsa cherry (*Grewia tenax*), mountain spike thorn (*Gymnosporia spinosa*), khejri, kikar (*Prosopis juliflora*), pilavapilu (*Salvadora oleoides*), rohida (*Tecomella undulata*) and jujube are suggested for cattle and livestock's feeding purpose due to higher palatability ratings of leaves which remain green in hot arid conditions (Ganguli et al. 1964). For management perspectives, the arrangement of these three elements such as horticultural crops, trees and pasture is a prerequisite for minimizing the competitions for natural resources among them.

2.2 AFS in Semiarid Tropics

Semidry tropics are extensively distributed in the area of around 2.1 billion hectares in the world. Ten percent area of semiarid is contributed by Indian sub-continent which is associated with 72 million hectares of vertisols (Burford and Virmani 1983; Murthy et al. 1982). Mango, guava, aonla, ber, custard apple (*Annona squamosa*), tamarind (*Tamarindus indica*), sapota (*Manilkara zapota*), jamun (*Syzygium cumini*), etc. are very promising fruit trees in terms of utilization from both nutritive and medicinal purposes under harsh climate. Furthermore, development of superior varieties for drought resistant and high yielding is the major concern in the area which can open the door for enhancement of productivity and health of soil along with microclimate amelioration with sustainable productions of some nutritive fruits for peoples. With the deciduous nature of trees which can make soil productive through addition and decomposition of leaf litter and another residue into soil organic matter (Hiwale 2004; Raj et al. 2016; Jhariya et al. 2018a; Meena et al. 2018), these systems can convert unproductive wasteland and degraded land to productive and cultivable lands.

2.3 AFS in Humid Tropics

Humid tropics are characterized by warm climate with high level of humidity accompanied by higher rainfall (> 1000 mm) and have ultisols and oxisols types of soil orders. Southeast Asia, Africa and Central America are the major geographical distributions of humid tropics. Kitchen garden, hedgerow system, multi-strata tree garden, plantation crop combination, etc. are the major AFM practiced in this region. Homegarden or kitchen garden is the most prevalent type of AFS prevalent in high rainfall areas having a combination of various multistory annual and perennial crops along with livestocks around the homestead. Similarly, a combination of some plantation crops like coffee, cocoa, coconut, rubber, oil palm, spice and fruits crops, etc. with shade-loving crops is another type of AFS in the form of plantation tree-crop combination. Moreover, another type of prevalent AFM such as multistratum tree garden is characterized by various species of multipurpose nature with no organized planting arrangements. The production under different agroforestry models under tropical condition has been mentioned in Table 3.

3 Climate Change: A Global Concern or Perspective

Climate change is not a recent phenomenon, and it has changed throughout history. However, because of human interventions, the change has become alarming and devastating. A human-caused anthropogenic impact on climate has been seen through emissions of GHGs (CO_2, nitrogen oxides, methane, water vapour, etc.) through various sectors such as power stations (21.3%) which is followed by industrial process (16.8%), transportation (14.0%), agriculture sectors (12.5%), fossils fuel (11.5%), domestic, economic and allied sources (10.30%), land utilization and burning of biomass (10%) and disposal of waste material (3.4%), respectively (IPCC 2015) (Fig. 2).

As we know, some practices like fuel burning (gas, coal and oil), changing land utilization and deforestation cause continuous emission of GHGs. Among all gases, CO_2, methane and nitrous oxide are considered most potent GHGs (Fig. 3) contributing 72%, 18% and 9%, respectively, in the emissions of GHGs (IPCC 2015). The concentration of atmospheric CO_2 has been increasing since pre-industrial era

Table 3 Production of multipurpose trees under different agroforestry models in major tropics

Tree combinations of AF model in different climates	NPP	References
NPP of above ground		
Plantation crop combination comprising coffee and shade trees in the humid climate of Colombia	8800 kg ha^{-1} year^{-1}	Bornemisza (1982)
Plantation system of mangium (*Acacia mangium*) in the humid climate of Malaysia	18,000 kg ha^{-1} year^{-1}	Lim (1985)
Plantation system of mangium in São Paulo University of Brazil	37 mg C ha^{-1} year^{-1}	Laclau et al. (2008)
Plantation system of loblolly pine (*Pinus taeda*), Gympie messmate (*Eucalyptus cloeziana*) and miombo woodland stands	14.1, 19.7 and 5.9 mg C ha^{-1} year^{-1}	Guedes et al. (2018)
Monoculture stands of loblolly pine in the coastal plains of North Carolina	20–25 mg C ha^{-1} year^{-1}	Sampson et al. (2008)
Plantation system of subabool in the humid climate of Hawaii	25,000 kg ha^{-1} year^{-1}	Pound and Cairo (1983)
Hedgerow intercropping comprising Mexican lilac (*Gliricidia sepium*) in the moist subhumid climate of Nigeria	3750 kg ha^{-1} year^{-1}	Bahiru et al. (1988)
Plantation system of subabool in the subhumid climate of India	38,200 kg ha^{-1} year^{-1}	Mishra et al. (1986)
Plantation system of kikar in the dry subhumid climate of India	30,000 kg ha^{-1} year^{-1}	Gurumurti et al. (1984)
Woodland system of honey mesquite (*Prosopis glandulosa*) in the arid region of the USA	3700 kg ha^{-1} year^{-1}	Rundel et al. (1982)
Leaf production		
Plantation system of mangium in the humid climate of Malaysia	3060 kg ha^{-1} year^{-1}	Lim (1985)
Hedgerow intercropping comprising Mexican lilac in the moist subhumid climate of Nigeria	2300 kg ha^{-1} year^{-1}	Agboola (1982)
Plantation system of subabool in the subhumid climate of India	2300 kg ha^{-1} year^{-1}	Mishra et al. (1986)

(280 ppm in the year of 1750) to the industrial revolution (379 ppm in the year of 2005), and today (2017) the figure is 407.62 ppm. Therefore, it clearly indicates how the concentration is increasing which results in the rising of temperature and leads to global warming. GHG emission leading to global warming has significant influence over ecosystem services as well as biodiversity of the concerned region (Fig. 4). Higher level of global warming alters the hydrological cycle of the concerned site leading to production of heat stress for living organism. Under such conditions, most of the species becomes vulnerable towards extinction. Therefore, the major indicators for climate change are the rise in global mean temperature, melting of ice, ocean acidification and continuous rise in sea level which results in

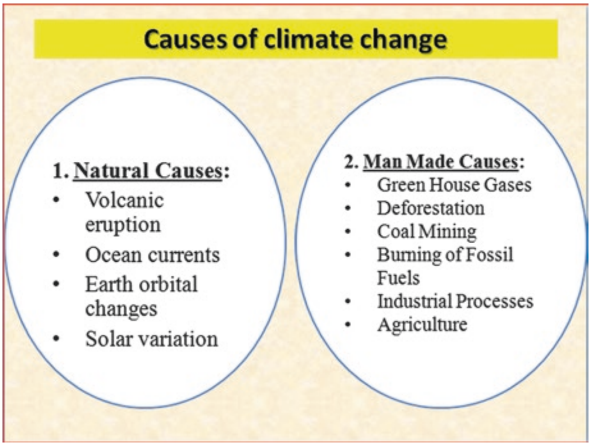

Fig. 2 Cause of climate change. (Riphah 2015)

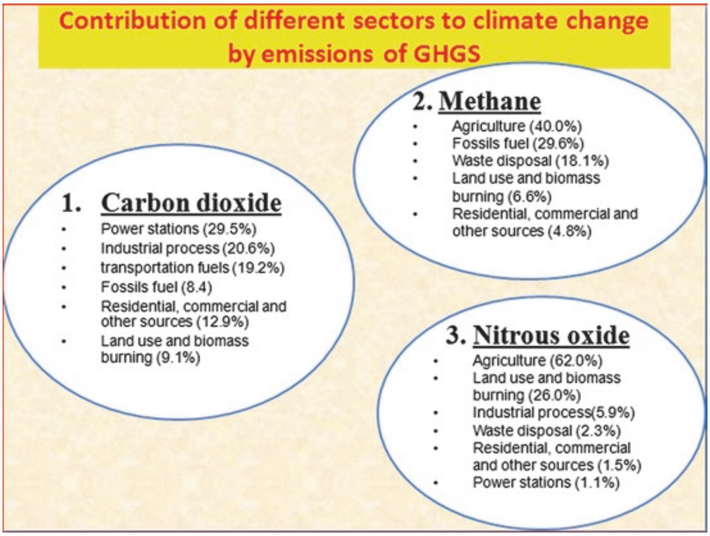

Fig. 3 Percentage share of different sectors in GHG emission in the world. (IPCC 2015)

a more frequent occurrence of flood, drought, fire, hurricanes, etc. that claimed hundreds of lives and property.

4 Agroforestry Under Changing Climate

Today, climate change is not only affecting agriculture and forestry, but it is disturbing several models of AFS in terms of reduction in productivity, profitability and sustainability. Agroforestry consists a variety of annual and perennial plants with some livestocks resulting in more complex and diverse interaction in comparison to monoculture systems. Extreme weathers like severe temperature, humidity and high CO_2 concentration affect all these organisms including microbial and insects which are associated with AFS. Therefore, each and every component of agroforestry (woody perennial trees, herbaceous crops and livestocks) systems response depends upon climate. It has been reported that selection of suitable species under AFS schemes helps to reduce a considerable amount of CO_2 in the atmosphere. Therefore, combating climate change is the secondary role played by AFS apart from giving economic benefits (Fig. 5). However, the existence of traditional models and improved models along with their management practices according to prevailing weather can upsurge the deleterious impact of climate change on different life form components (tree, crops and pasture/livestocks) (Fig. 6).

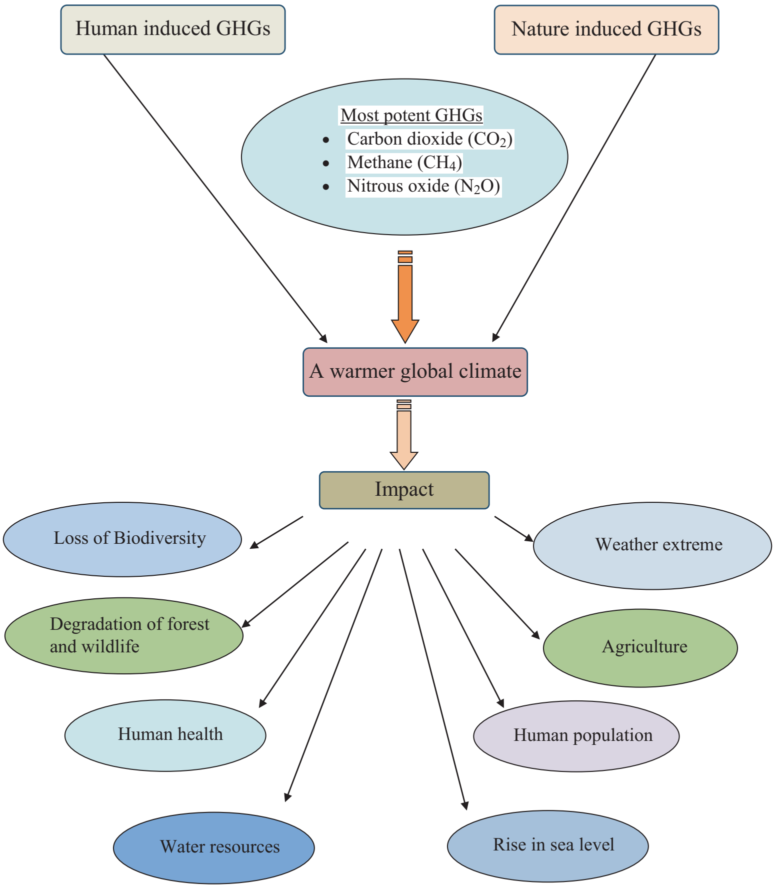

Fig. 4 GHG impact on ecosystem and biodiversity. (del Rio 2012)

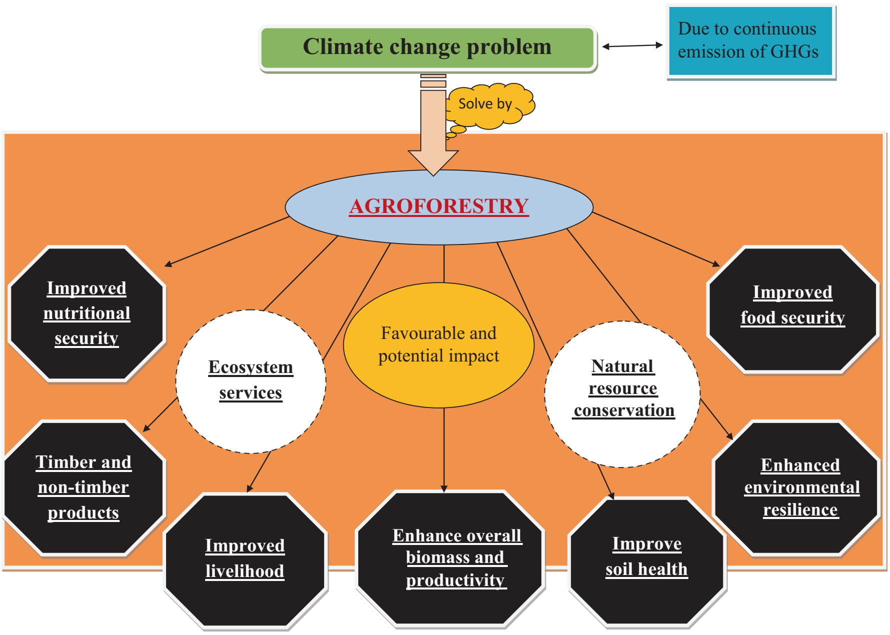

Fig. 5 Agroforestry impacts and climate mitigation. (Pachauri 2012; Swamy and Tewari 2017)

5 Agroforestry Solutions for Climate Change

Indeed, the practices of different AFM undoubtedly can reduce atmospheric CO_2 concentration in the course of fossil fuel substitution. Due to the complex nature of AFS, it can absorb atmospheric C and store in different components such as bole, branch, foliage and root. Thus, agroforestry is the type of C farming system in which ambient C can be sequestered in soil and vegetation with the management of the natural resources like light, land, water and nutrient along with the provision of food security under changing climate with landscape restoration (Jhariya et al. 2018b; Yadav et al. 2017).

The mechanism of C fixation during photosynthesis, storage through C sequestration and removal of C by respiration of both above-ground and below-ground biomass is depicted in Fig. 7. Similarly, internal transfer of C from above to below ground, i.e. soil, is another important area where more C can be added. The option of the fast-growing tree with high yield under short rotation forestry programme gives greater biomass through higher CO_2 absorption. As per one estimate, the storage capacity of C under AFS is 0.3–15.2 mega C/ha/year in the world, and according to Nair et al. (2011), the storage capacity was found to be maximum in humid tropics as compared to other areas of high rainfall.

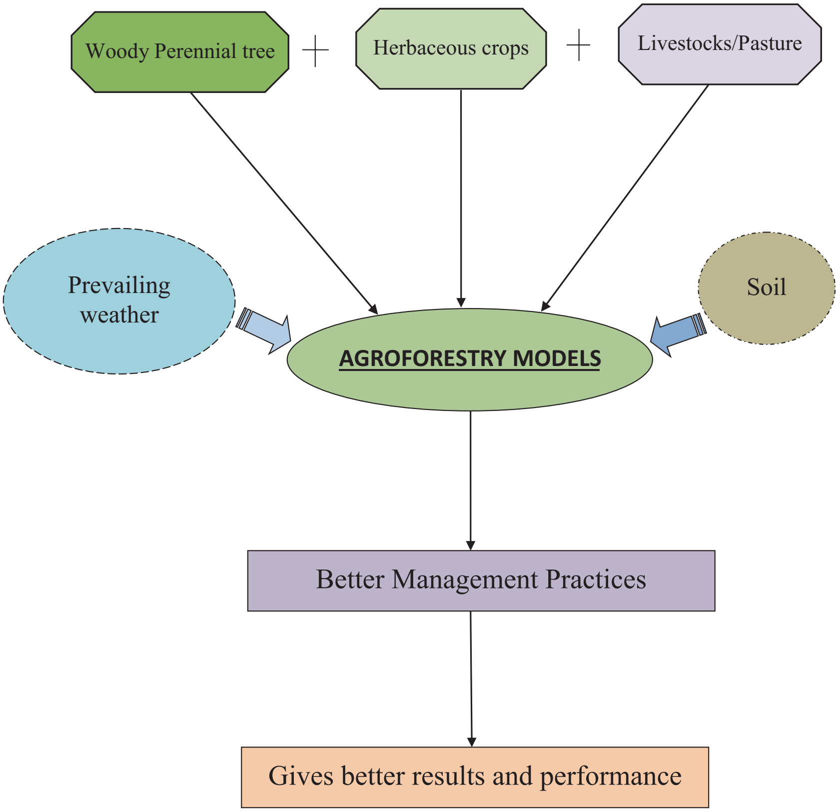

Fig. 6 General models for agroforestry performance. (Nair 1993)

6 Addressing Food Insecurity Through Agroforestry

Agroforestry is a better practice of a farming system for maintaining biodiversity along with the diversified production of food, fruits, fibres, etc. and maintaining food and nutritional security. However it has some limitations. Apart from its inherent limitation, the scope of agroforestry has widened up in the era of climate change as secondarily it helps in mitigation and adaptation of climate change (Fig. 8). Incorporation of horticulture trees under horti-based AFS could potentially enhance both productivity and profitability in terms of producing fruits and vegetables which are the good sources of essential nutrition (protein, vitamins, minerals, etc.) for peoples and fulfil the requirement of minimum balance diet per day per capita (85 g for fruits and 220 g for vegetables) (Roy 2011). Similarly, several fruit trees comprising mango, aonla, citrus, papaya (*Carica papaya*), etc. are very nutritious and have essential biochemical substances for healthy life. Thus, the addition of some horticultural crops (fruits, vegetables, etc.) guarantees food and nutritional security through provision of multifarious benefits as edible fruits, vegetables, etc. to

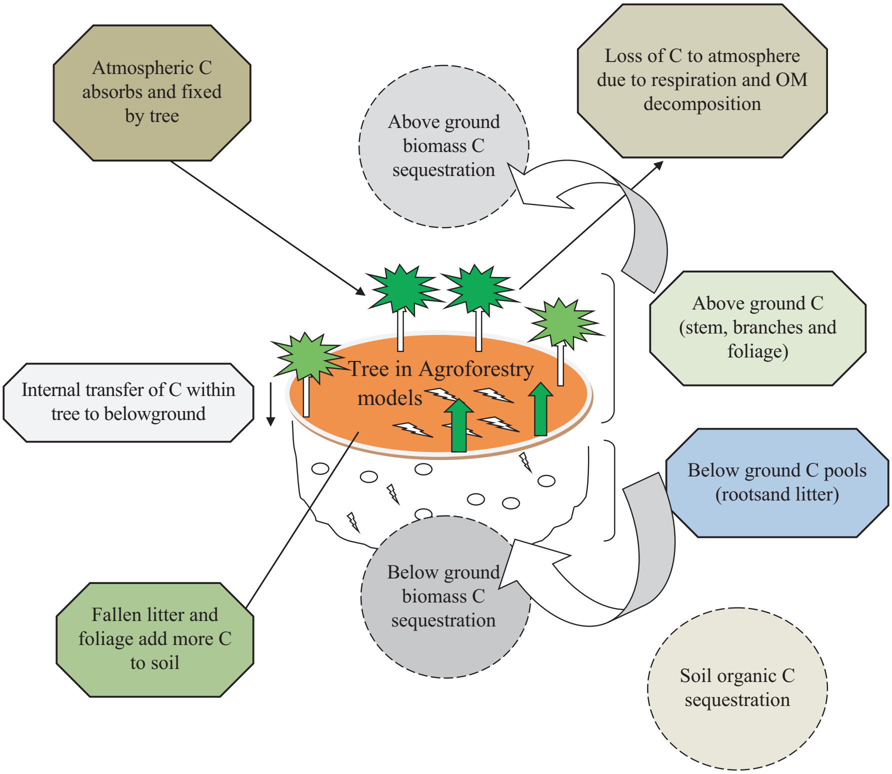

Fig. 7 Role of agroforestry in C sequestration. (Atangana et al. 2014b; Nair 2012)

farmers and enhances employment along with socio-economic development (Samara 2010).

7 Agroforestry for Wasteland Reclamation

The land is the non-renewable and important natural resource for the existence of civilization and cultivation of agriculture. A faulty land use practice (non-sustainable land management) leads to degradation causing loss of soil fertility, soil and water erosion and other uncountable ecosystem problems. This can affect the overall productivity and profitability of any farming practices. Therefore, integration of perennial trees in AFS can pave this problem of land degradations through addition and decomposition of organic matter to the soils, enhancement of fertility that results in close and efficient nutrient cycling and maintaining the health of the ecosystems. Thus, reclamation, restoration and development of wasteland are another area of scope and potential of AFS (Jhariya et al. 2015; Datta et al. 2017).

Salinity and sodicity are few of the major types of wasteland that not only affect the life cycle of trees and crops but also reduce the productivity of that land.

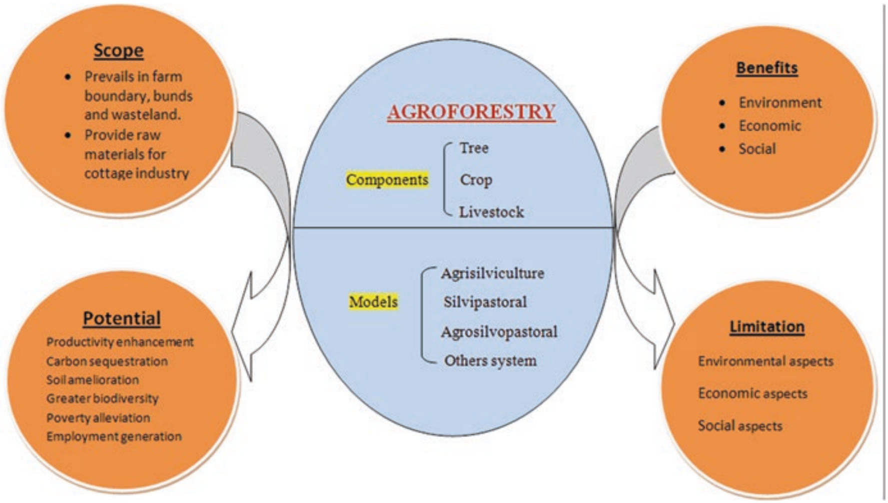

Fig. 8 Schematic representations of AFS. (Sinclair 1999)

Waterlogging (marshy) land, degraded pasture/grazing land, land under the practice of shifting cultivation, ravine land, mining and industrial lands, etc. are another category of wasteland that spread throughout the world. Soil runoff, erosion, desertification, acidification, the occurrence of frequent floods, drought, loss of soil nutrients and productivity, loss of biodiversity and poverty are the major impacts of land degradation. Therefore, this wasteland is to be utilized through the adoption of different AFM that can make a scope for multiple uses of this land. The incorporation of suitable fodder trees, bushes, pasture, grasses and fruit crops is the viable option for both reclamation and economic gain. Thus, agroforestry for a different form of wasteland areas is summarized in Table 4.

8 Prospects of Agroforestry in Soil Management

Soil is that which we call the soul of infinite life. Definitely, soil gives unique ecosystem services to sustain life on the earth. In AFS, close-type nutrient cycling exists rather than the open-type nutrient cycling in which chances of loss of nutrients are prominent under the sole type of cropping practices. Soil provides ecosystem services like regulation of soil structure, function, efficient nutrient cycling and C sequestration and acts as a habitat for different soil organisms which plays a vital role in good soil health. The schematic representation of ecosystem services provided by soil under AFS is depicted in Fig. 9.

From the array of beneficial effects of agroforestry on soil, it is a matter of fact to discuss the problems and prospects of agroforestry components such as trees on productivity and health of the soil in the tropics. Tree adds organic inputs through its litter components and roots as decaying of both can enhance the presence of C

Table 4 Wasteland and its reclamation by different species under AFM

Type of wasteland	Reclamation through AF	References
Salt-affected soils	Kikar + swamp grass (*Leptochloa fusca*)-based silvipastoral model and forest red gum tree (*Eucalyptus tereticornis*)-, poplar (*Populus deltoides*)-, teak (*Tectona grandis*)- and beach oak-based AFM. Fruit trees like jujube, aonla, pomegranate, tamarind, etc. and grasses like smut grass (*Sporobolus indicus*), doob grass (*Cynodon dactylon*) and buffel grass (*Cenchrus ciliaris*) based silvopastoral, agrisilviculture, agrisilvopastoral and hortipastoral systems, etc.	Singh et al. (1994)
Alkali soils	MPTs like kikar- and babool-based AFS. Farash (*Tamarix articulate*), pilavapilu, arjun (*Terminalia arjuna*), karanj (*Pongamia pinnata*), forest red gum tree and common sesban (*Sesbania sesban*) are another tree species suitable for alkaline soils. Fruit trees like guava, date palm (*Phoenix dactylifera*), tamarind, jamun, etc. and grasses like rhodes grass (*Chloris gayana*), doob grass, species of millets, etc. based silvopastoral, agrisilvopastoral, hortipastoral systems, etc.	Ahmed (1991)
Acid-affected soils	Suitable tree species like silk tree (*Albizia chinensis*), *Ficus* species, Himalayan mulberry (*Morus serrata*), elm tree (*Ulmus nepalensis*), etc. legume species includes centro (*Centrosema pubescens*), stylo (*Stylosanthes guianensis*), calopo (*Calopogonium mucunoides*), tropical kudzu (*Pueraria phaseoloides*), *Desmodium* species, etc. and suitable grasses species like crown grass (*Paspalum notatum*), kyasuwa grass (*Pennisetum pedicellatum*), mission grass (*Pennisetum polystachion*), etc. based silvopastoral system	–
Ravine land	Suitable trees species like khejri, *Acacia* spp., shisham, male/solid bamboo (*Dendrocalamus strictus*), kachnar (*Bauhinia purpurea*), etc.; fruit trees comprising mango, aonla, guava, beal (*Aegle marmelos*), pomegranate, etc.; and suitable grasses species like marvel grass (*Dichanthium annulatum*), blue panicgrass (*Panicum antidotale*), kyasuwa grass, buffel grass, etc. based silvopastoral, hortipastoral, silvihortipastoral systems	Meena et al. (2015a)
Arid desert and sand dunes	Suitable tree species like kikar, neem, umbrella thorn acacia, etc. and fruit trees comprising ber, beal, pomegranate, tamarind, date palm, etc. based silvihorticulture systems. Suitable grass species like buffel grass, birdwood grass (*Cenchrus setigerus*), etc.	Tewari (2016)
Waterlogged, marshlands and swamps. Swampy and wet lands	Suitable tree species comprises of shisham, *Eucalyptus* species, Indian willow (*Salix tetrasperma*), Euphrates poplar or desert poplar (*Populus euphratica*), etc.; suitable grass species comprise Nadi blue grass (*Dichanthium caricosum*), crowngrass, Para grass (*Brachiaria mutica*), etc.; and legumes comprise common sesban, wild tantan (*Desmanthus virgatus*), perennial soybean (*Glycine wightii*), etc.	–
Mine-affected land	Species such as babool, black siris, neem, khair (*Acacia catechu*) and fruit trees like ber, etc. are suitable for this area	–

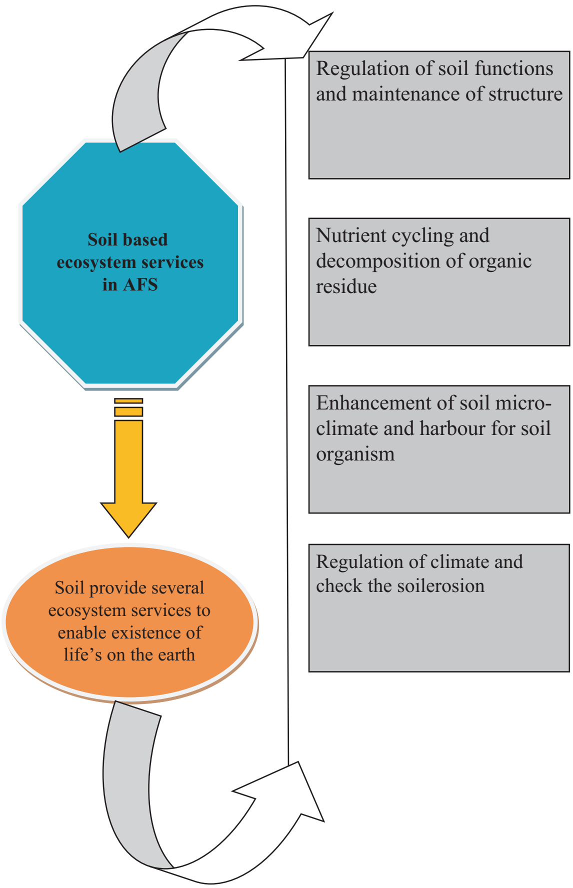

Fig. 9 Ecosystem services by soil under AFS. (Udawatta et al. 2017)

which results in the occurrence of a vast range of soil-inhabiting organisms (earthworms, etc.). Further, their interactions improve the status of nutrients and fertility of soils (Bertin et al. 2003; Dadhich et al. 2015). Also, accumulation of C in soils depends on the type of tree species involving litterfall, texture of leaf litter, decaying of organic matter, decaying agents and, in broad sense, we can say overall management of agroforestry practices that can affect not only soil health but also sequestration capacity of C. Similarly, tropical soil is comparatively more diverse in terms of biomass, C (which is derived by decomposition of organic matter) and microorganism than in temperate region.

9 Agroforestry and Soil Health: A Linking Concept

The soil is intricately related with various components of the environment such as lithosphere (parental rocks and earth crust), hydrosphere (water body), atmosphere (through cycling of gases) and biosphere (through flora and fauna), and their proper

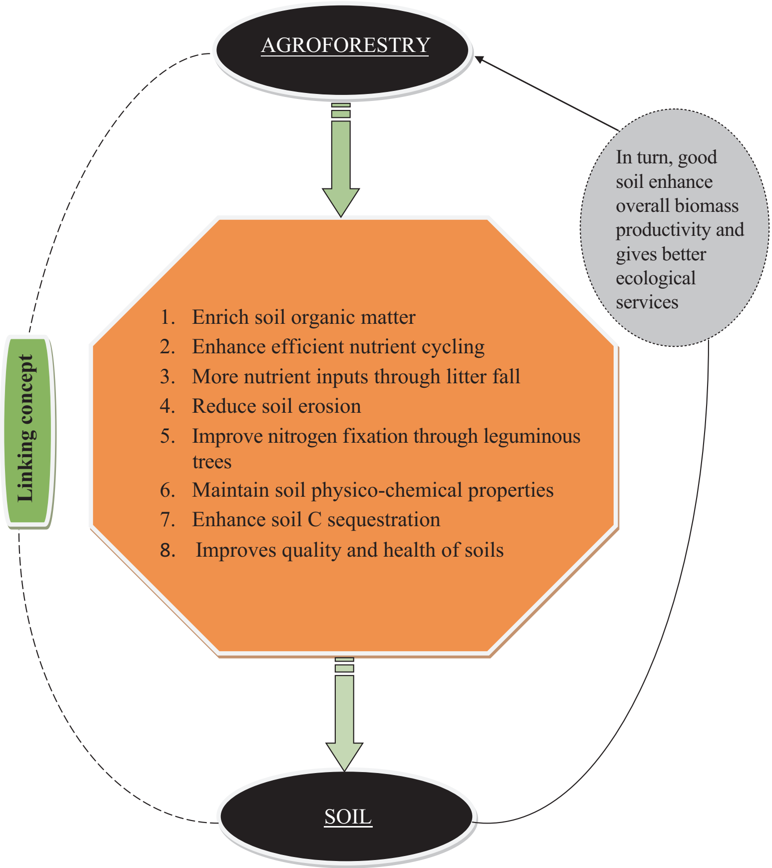

Fig. 10 Agroforestry and soil – a linking concept. (Barrios et al. 2012; Udawatta et al. 2017)

health services are prerequisites for better productivity, quality and sustainability. Soil forms habitat for flora, and its health can be uplifted through the incorporation of various types of multiple and complex farming practices rather than sole type and monoculture farming system. Agroforestry suits for the multiple and complex types of the farming system which can enhance soil fertility and productivity through the addition of organic matter and performs close-type nutrient cycling rather than open-type nutrient cycling in monoculture (sole) farming systems. Thus betterment of AFS and soil health are linked in various ways. For example, good management of AFS can enrich soil organic matter, enhance efficient nutrient cycling, add more nutrient inputs through litter fall, reduce soil erosion, enhance nutrient input from atmosphere, improve nitrogen-fixing ability through incorporation of leguminous trees, maintain soil physicochemical properties, enhance soil C sequestration in climate change scenario and overall improve quality and health of soils (Fig. 10).

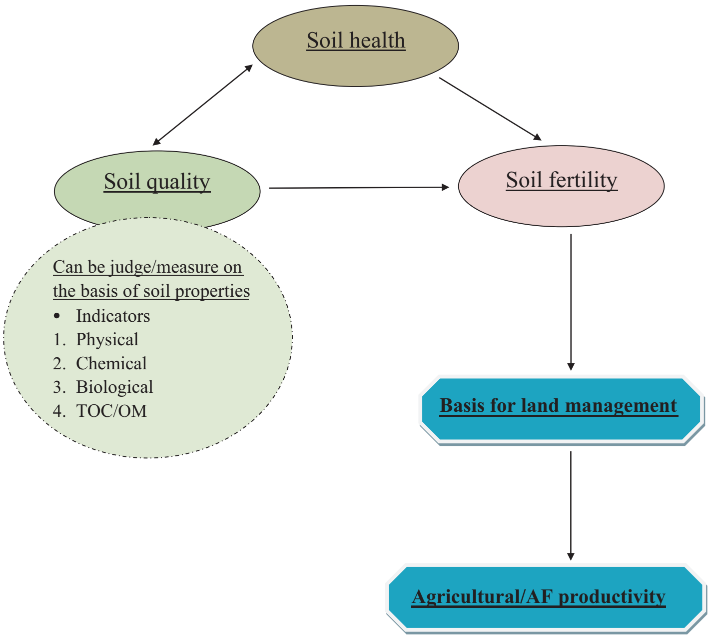

Fig. 11 Synergies between soil health, fertility and productivity under AFS. (Dollinger and Jose 2018; Barrios et al. 2012)

10 Synergies Between Soil Health and Productivity Under AFS

There is the nexus between soil health, quality, fertility and production potential of various AFM. Overall agroforestry productivity depends on quality and health of soil which can be judged and measured by soil indicators or properties such as soil physicochemical attributes and soil biota that reflects the fertility of soil, which is the basis of land management practices and indicates productivity of any model (Fig. 11). Good soil health reflects better ecosystem services that maintain environmental health along with human health (and other organisms and soil-inhabiting organism). Similarly, several management practices such as agroforestry, multiple cropping, cover cropping, non-tillage practices and incorporation of organic manures can potentially enhance the quality and health of soil which is the pillar of higher productivity along with environmental quality (air and water quality) (Fig. 12).

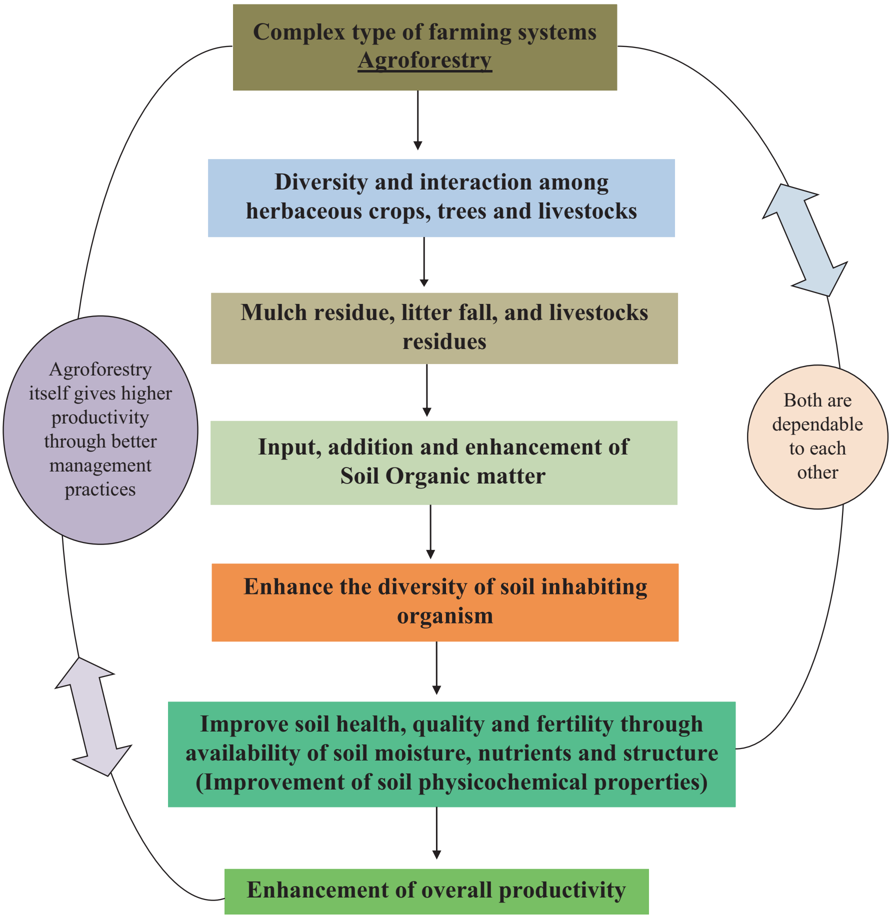

Fig. 12 Nexus between agroforestry, soil health and productivity. (Dollinger and Jose 2018)

11 Ecosystem Services of AFS

Agroforestry provides both ecosystem services and disservices. Ecosystem services comprise of four potential elements, viz. provisioning, regulating, supporting and cultural services produced by the adoption of AFS rather than disservices (Fig. 13). Moreover, agroforestry gives greater biodiversity and higher biomass productivity which shows the absorption capacity of atmospheric CO_2 which results in better environment and provides healthy ecosystem services. Both tangible and intangible benefits of AFS are the major component of ecosystem services. Tangibles, i.e. direct services, include timber, fuelwood, firewood and other non-timber forest produces like gum, fodder, katha, etc. On other side, soil water conservation, watershed management, efficient nutrient cycling, etc. are the major services by AFS that

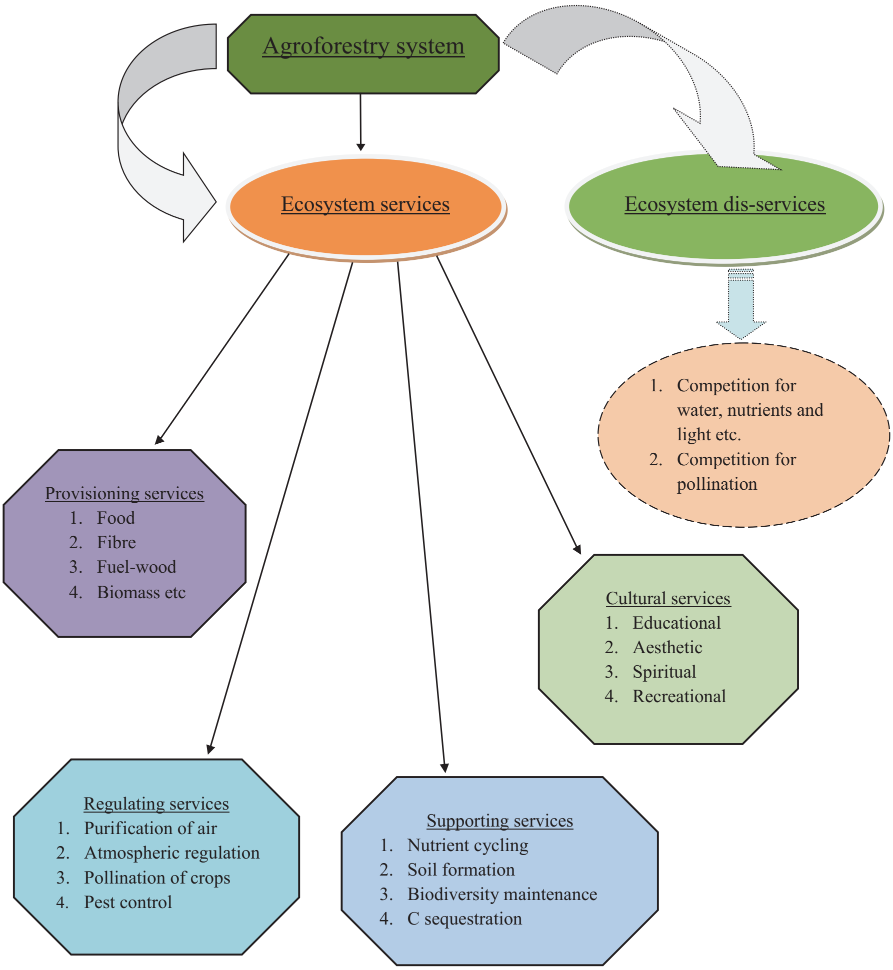

Fig. 13 Ecosystem services and disservices in AFS. (Kuyah et al. 2017)

come under indirect and intangible benefits. Among them, gum production from trees can enhance economic gain of farmers and results in retention of trees either on field bund or as scattered. For example, babul-based bund plantation in Chhattisgarh gives better utilization and economical viability through gum productions other than multipurpose and leguminous characteristics of trees (Das et al. 2014; Raj et al. 2015; Raj 2015a, b; Raj and Singh 2017; Meena and Meena 2017).

Agroforestry is well known for better ecosystem service provider through the provision of excellent economic incentive along with maintenance of biodiversity and environmental sustainability (FAO 2007). Also, agroforestry gives benefits in both spatial and temporal scale (Jose 2009). For example, incorporation of several AFM in the area of deforestation (removal of trees) can check the problem of soil erosion and prevent sedimentation of waterways that lead to protection of downstream ecology and biodiversity through beneficial ecological services (Pearce and Mourato 2004). Moreover, both C sequestration potential and better provision of ecosystem services of AFS give the foremost and good scope of research in the era of climate change (Oelbermann and Voroney 2011; Pagiola et al. 2008; Jhariya et al. 2015). Thus, farmers and peoples enjoy these ecological services at regional and global scales which are derived from multifarious AFS in different agroclimatic zones of the world (Jose 2009).

12 Agroforestry for Natural Resource Conservations

As we know, AFS are the very complex type of farming practices, help in resource conservation and their efficient utilization, give more profitable benefits and maintain ecosystem services by producing both tangible and intangible benefits to people. The management of agricultural land through the integration of some multipurpose and leguminous trees is the great choice for management and utilization of natural resources available in these models in different agroclimatic zones (Jhariya et al. 2018a; Varma et al. 2017).

In this context, the term agroforestry can be the best fit for better NRM. For example, AFM utilizes soil resource efficiency and reduce leaching of essential ions by holding the soil through deepest root systems of available trees which is effective for minimizing soil erosion and form close type of nutrient cycling. Therefore, agroforestry as complex and multifarious farming systems are a better performer for resource conservation than sole cropping of either crops or trees. Moreover, along with conservation, it will be profitable to farmers by producing several types of produce to sustain life and conserve biodiversity (Singh and Jhariya 2016). In this context, tree-crop interaction plays a major role. For example, better management practices of models along with a suitable combination of tree and crops could potentially reduce competition among agroforestry elements (tree, crop and livestock) for light, water, space and soil nutrient.

Among all resources, water deserves foremost and prime position for sustaining the life and proper development of plants. Thus the major question that has been raised is “Can adoption of agroforestry increase the water availability and uptake of crops and trees under varying climatic condition?”. Water use efficiency of the different AFM having trees and crops varies as per availability of water, prevailing climate and topographical condition of the sites. Management for better tree-crop interaction can enhance the water use and proper management of this resource. This is very prime research for the dry region where scarcity of water is prominent. Therefore, identification of suitable species combination and their management practices can optimize the absorption capacity of water (having essential nutrients and ions) and minimize the competitions among different life forms (trees, crops, grass, etc.) (Ong et al. 2006). Also, the main question in this context is how to enhance the resource capture and productivity under different combinations of crops and trees without affecting the yield potential of crops under the tree canopy in AFS. This can be resolved through an appropriate combination of species along with better model with leafing phenology and flushing (Huxley 1996). It may work efficiently on wasteland area.

13 Agroforestry and Livelihood Security

Recalling agroforestry for livelihood security, it will be a better choice to integrate various multipurpose and leguminous trees (and others) on farm field for guaranteed income and farm diversification through the delivery of several tangible products (timber and non-timber products) under continuous changing climate and extreme weather (WAC 2010). Livelihood security under AFS is a linking concept that provides profit and economic gains through combination of economically viable tree species (timber and fruit trees) along with annual herbaceous crops rather than sole cropping. Similarly, complex type of AFM such as homegarden could potentially diversify the outputs and sustain the peoples through provision of nutritious fruits, spice, vegetables, etc. for their household consumption along with economic gain by selling surplus productions in nearby market (Bellow et al. 2008; Meena et al. 2017).

In addition to improved and managed AFS, bund-based agroforestry can potentially uplift the socio-economic benefits along with environmental protections. For example, babul-based bund plantation is very effective for gum exudation and economically viable if the process of gummosis should be done by ethephon-induced scientific methods (Fig. 14). This system gives valuable and commercial gums in addition to timber and crop yield along with various environmental benefits due to leguminous nature. Thus

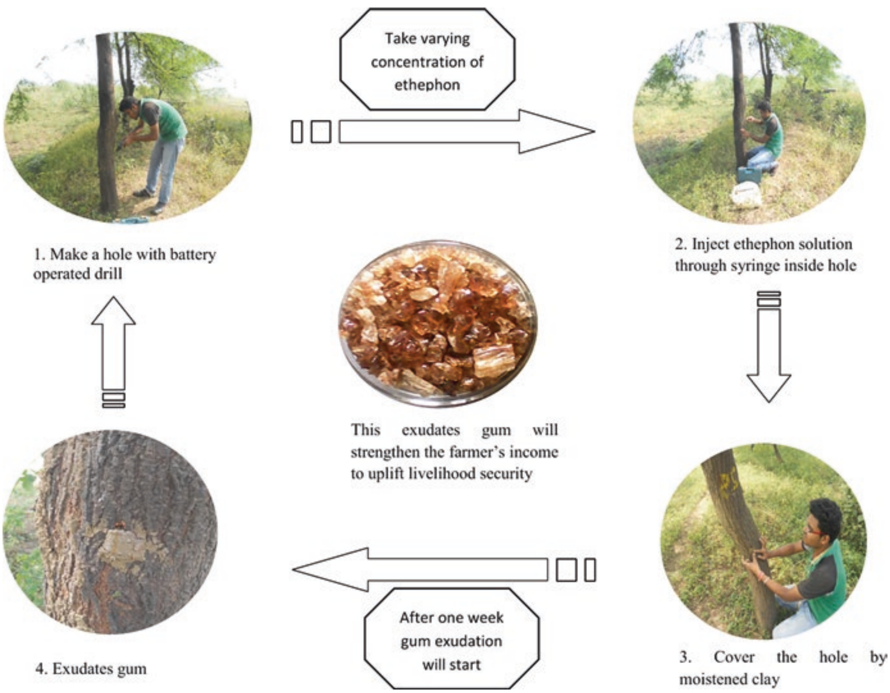

Fig. 14 Strengthening the farmer's income through ethephon-induced gum exudation. (Raj and Singh 2017)

gum tapping by using ethephon is not only economically viable but also conserves biodiversity too. Similarly, the integration of some lac hosting trees under AFS may open the door for economic gain. For example, the addition of only single tree of palash (*Butea monosperma*) under AFS would be viable for farmers for livelihood security through lac cultivation practices and produce 1.5–2.5 kg lac with annual income of 700–800 rupees per tree in central India region (Sridhar et al. 2015).

Likewise, apiculture-based agroforestry can strengthen the income of farmers by producing honey and maintaining diversity and health of honeybees which are natural pollinators (Painkra et al. 2016). Hence, there are various literatures that show agroforestry gives more benefit to the farming community in comparison to traditional farming and enterprises of forestry. Incorporation of agroforestry practices on waste and marginal land is also a good option/choice for better productivity and profitability for farmers. For example, under rainfed condition, the B:C ratio (3.28) of a 13-year-old aonla-based AFS on marginal land indicates more economic gain. Similarly, integration of poplar on both agricultural field and on the bund is more profitable for farmers and gives excellent economic return than sole cropping practice in upper Gangetic region of Punjab, Haryana and Uttar Pradesh (Ram Newaj and Rai 2005; Singh et al. 2014; Yadav et al. 2018). Also, economic profitability in terms of B:C ratio of different AFM in various agroclimatic zones of India is depicted in Fig. 15. As per the figure, the poplar + paddy (*Oryza sativa*) and

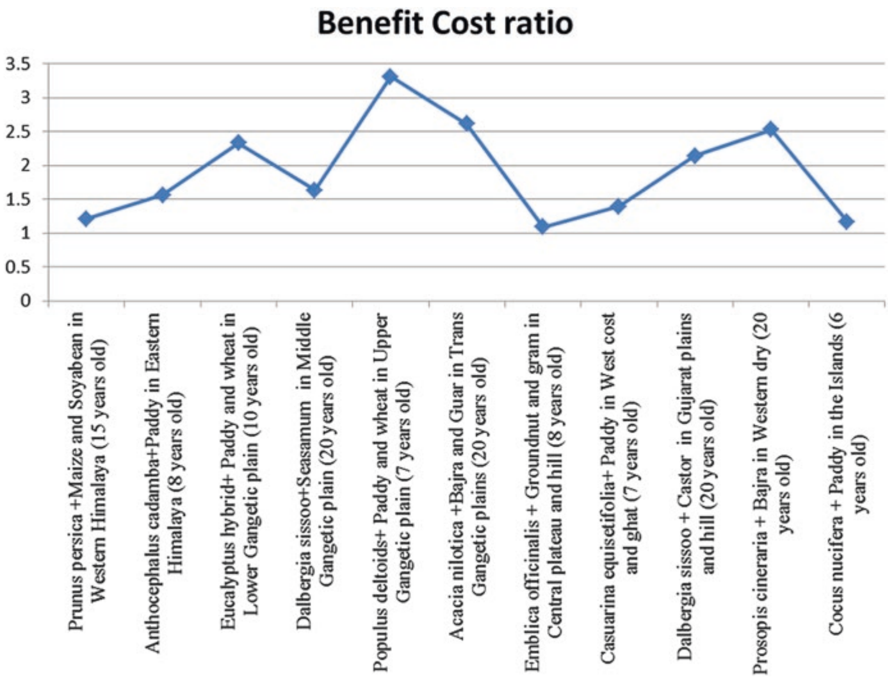

Fig. 15 Economic profitability as B:C ratio of different AFM in various agroclimatic zones of India. (Handa et al. 2016)

wheat-based AFM in upper Gangetic plain (7 years old) are more profitable for farmers through highest B:C ratio (3.31) followed by babool + bajra (*Pennisetum glaucum*) and guar-based AF system in Trans-Gangetic plains (20 years old) having 2.61, khejri + bajra-based AF system in Western dry (20 years old) having 2.53 and eucalyptus hybrid + paddy- and wheat-based AF system in lower Gangetic plain (10 years old) having 2.33 and least in aonla + groundnut- and gram-based AF system in central plateau and hill (8 years old) having 1.09.

14 Scientific Interventions and Policy for Agroforestry

Agroforestry is location specific, and the ecological adaptation of different models of agroforestry is a prime concern for researchers and policymakers. Policy should be in favour of targeting and promoting inclusion of trees in various abandoned and wasteland along with agricultural field and boundaries for the enhancement of land productivity and food and nutritional security along with both employment generation and environment protections. In this connection, a nationwide agroforestry policy has been formulated in 2014 by the Indian government to promote agroforestry across the country for sustainability. This will not only give better landscape but also minimize the health risk of people. Therefore government policy should aim for promotion and development of agroforestry, and this can be achieved easily through the intervention of private sectors and educational institutions. Although agroforestry has been embedded in national agroforestry programme, accordingly agroforestry research should be transformed from descriptive studies to more scientific-oriented research. This can open the door for better understanding about competition, complexity, profitability and sustainability of various AFM. This scientific intervention can maximize the productivity, profitability and sustainability of models under changing climatic condition. Furthermore, research scientist must go for technical research without considering the sociopolitical issue, and this can draw an attention to government and policymakers for drawing and implementing a suitable and favourable policy for existing and improved AFS.

15 Conclusions

The scope and potential of agroforestry are now recognized at the world level. As we know, food insecurity, natural resource conservation and land degradation are the major concerns today under changing climate faced by the world. This can affect global productivity along with the biodiversity of that particular region. In this context, agroforestry is a good option and curb the continuous emission of GHGs by sequestration process of atmospheric C and store in the form of biomass (for productivity), mitigate climate change and gives multifarious products as timber and non-timber products as profits to poor farmers. Thus, agroforestry products give financial benefits to poor farmers along with various ecological services. Also, effective government policy for the promotion of agroforestry, wherever possible, can maintain forest covers on the whole landscape which is better for environmental and ecological security and moving towards sustainable development.

16 Future Prospects of AFS

Agroforestry has three attributes such as adoptability (based on location specific), sustainability (without depleting natural resources) and profitability (term of economic gain to farmers) on which both present and future generations depend. Similarly, agroforestry has been popularized among farmers, peoples and policymakers throughout the world, and it gives an immense potentiality for future benefits to people by provision of direct and indirect benefits through ecological services for better landscape. The multifarious services and benefits of AFS show significant promise towards poor farmers and policymakers.

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Soil and Water Conservation Techniques for Sustainable Agriculture

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Abstract

Natural resources of the country are humiliating due to biotic and abiotic pressures. Around 146.8 Mha land was estimated under degraded land of India by National Bureau of Soil Survey and Land Use Planning (NBSS&LUP). Among different land degradation categories, soil erosion through runoff is the major threat for degradation of soil and water resources. It results into 5.3 billion tonnes soil loss annually. Detached soil carry with runoff water and siltation occurs in water reservoirs; it results in depletion of reservoirs storage capacity by 1–2%. Intensive agricultural practices accelerate the rate of soil erosion. In this context, use of groundwater (by drilling tube wells) in high rates also depletes the groundwater level. The groundwater level of 65% open wells was depleted. Such conditions negatively impact on productivity of agriculture crops. High rate of runoff degrades soil health and ultimately decreases the food production of the country. Vegetation and mechanical measures need to be applied separately or in combination for solving such problems of natural resource (soil and water) degradation. Along with such measures, some improved techniques may need to be designed for judicious management of natural resources. Although there were many schemes/programmes/missions also running through government and non-governmental organization to combat these problems, we have to work for the policy on conservation of natural resources through sustainable agricultural practices.

Keywords

Ecological sustainability · Natural resources · Soil erosion · Soil and water conservation · Sustainable agriculture

Abbreviations

C	Carbon
CAZRI	Central arid zone research institute
FYM	Farm yard manure
ICAR	Indian council of agricultural research
MPTs	Multipurpose tree species
N	Nitrogen
NBSS&LUP	National Bureau of Soil Survey and Land Utilisation Planning
NFT	Nitrogen fixing trees
OM	Organic matter
SALT	Slopping agricultural land technology
SCT	Staggered contour trenches
SOM	Soil organic matter
SWC	Soil and water conservation
WUE	Water use efficiency

1 Introduction

Sustainable and resilient agricultural systems may be achieved by controlling soil degradation and muzzling changing climatic conditions. The soil degradation states that the adverse change in soil qualities reduces productive capacity of land (UNEP 1999; Bhattacharyya et al. 2015; Gomiero 2016; Jhariya et al. 2018a). Degradation of land generally indicates the temporary or permanent drop in the productive ability of the land (UN/FAO definition). Degradation may instigate due to miss use of land resources. Deforestation, intensive agricultural practices and other developmental activities may hasten soil degradation through flooding, salinization, prolonged drought period, water logging, high rate of runoff and acidification. Overgrazing, distraction of natural flora, urbanization and intensive agricultural practices are some other causes of land degradation. In India, ~146.8 Mha area is covered by different categories of degraded land (NBSS&LUP 2004; Anonymous 2010a, b). Soil loss due to the water action is the most serious problem in India, as it far exceeds the natural soil formation rates (Mandal and Sharda 2011; Saroha 2017; Dadhich et al. 2015).

Deforestation is the main causal factor of soil erosion. Roots of the trees, shrubs and grasses hold the soils in its place and therefore prevent soil erosion. But due to extensive deforestation, soil erosion is becoming a vital danger in the areas, where soils are of light and medium textured. Soil loss takes place at the rate of ~16.4 ton $ha^{-1}year^{-1}$, which results in loss of soil of about 5.3 billion tonnes annually throughout the country (Bhattacharyya et al. 2015). Whereas the rivers and reservoirs account for 5334 M tonnes soil lost annually, out of that, 29% soil is being lost into the sea, 10% gets deposited in the water bodies and the remaining 61% is detached from one place and deposited at another place. It affects agriculture production badly. The storage capacity of major reservoirs is getting lost by 1–2% every year due to high siltation rates. Loosening and detachment of soil particles and their movement from one place to other along with their deposition by different agencies (wind and water) are known as soil erosion.

The 13 river basins, i.e. Indus, Ganga, Brahmaputra and Barak, Narmada, Tapti, Brahmani-Baitarani, Mahanadi, Godavari, Krishna, Pennar, Cauvery, Mahi and Sabarmati, are mainly accountable for the total water resources of India (CGWB 2016). In the year 2015, 1869 billion cubic meter (BCM)/year was available water, out of that 1123 BCM/year was usable water in India, whereas 690 BCM/year was accounted as surface water and 433 BCM/year as groundwater. However, 398 BCM/year was accounted as net annual groundwater availability and 35 BCM/year as natural discharge (Suhag 2016). India developed a Blueprint for National Water Accounting Framework to use water resources efficiently. Collection of data on water resources and environmental, economic data leads to database generation which would help to develop a decision support system (Anonymous 2017; FAO 2018).

Madhya Pradesh state is also facing a problem of rapid soil erosion in its northern part along the Chambal, Sindh and its tributaries. Total geographical area of Madhya Pradesh is 3,08,641 and 1,82,870 km^2 (59%) area is degraded across the state (Anonymous 2010a). Land degradation due to ravines in the Morena, Bhind, Shivpuri, Ujjain, Gwalior and Mandsaur district is a critical problem and seen as a main obstacle in lowering crop productivity. Since the soils of this area are light and devoid of vegetation, thus water easily erodes the soil resulting into erosion. The total 1502.06 km^2 area comes under ravine infestation in the state (Anonymous 2010b). About 20% land of Datia district, Madhya Pradesh is under ravines (SPWD and SAMBHAV 2004). Sheet erosion, gully erosion and stony waste were the soil erosion categories reported by Tagore et al. (2012) in Rajgarh district of Madhya Pradesh. They also reported 58365 ha area falls under sheet erosion followed by 1519 ha under gullied and 923 ha under the stony waste. The study was aimed at to study the problems caused due to the soil and water erosion in country's agriculture production and find out the sustainable measures for mitigating the soil and water erosion problems.

2 Phases, Mechanism and Types of Soil Erosion

2.1 Soil Erosion by Water

Soil erosion is the phenomenon caused by various environmental forces and factors that leads to soil deterioration by shifting of soil from one place to other place. The rate of soil erosion is boosted due to high intensity rainfall, high wind speed, steep slope, low plant cover and high temperature. Whereas, soil organic matter (SOM), soil texture, structure, water holding capacity, exchangeable cations and clay minerals may also affect the soil erosion (Pimentel and Burgess 2013; Lal 2001; Meena et al. 2016). Soil erosion caused by water encompasses three key basic phases, i.e. detachment, transportation and deposition (Fig. 1).

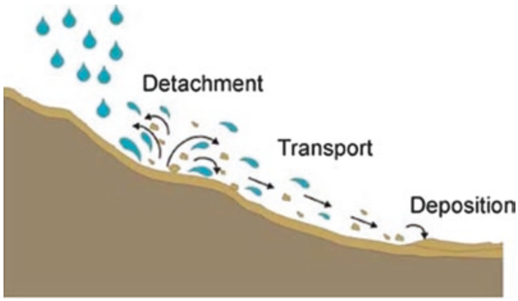

Fig. 1 Three main basic phases of soil erosion losses through water

2.2 Mechanics of Soil Erosion

- *Hydraulic action:* The force exerted by the air in the vacuum.
- *Abrasion:* Shear force of water to wash the soil.
- *Attrition:* Mechanical breakdown of loads.
- *Solution:* Chemical action between soil and water.
- *Transportation:* Carrying of soil particles/ matter from one place to other. It depends on velocity of runoff and type of load (soil material).
- *Deposition:* Whenever the velocity is lower than the carrying capacity, then the loads will be deposited on the bed of the water course.

2.3 Types of Soil Erosion

Splash, sheet, rill, gully, slip, tunnel, stream bank and seashore erosion are the main types of the soil erosion (Fig. 2) (Fernandez-Raga et al. 2017; Govers et al. 2017; Bandyopadhyay et al. 2013; Ghosh et al. 2013; Hegde 2010; Anonymous 2008; Pathak et al. 2005; McCauley and Jones 2005; Ashoka et al. 2017).

(i) *Raindrop/Splash Erosion*

Falling raindrop on the soil surface breaks the soil aggregates, and soil particles splashed on soil surface are known as splash erosion. It is considered to be the first step in the erosion by water. This process can only move soil particles a few centimetres away from its place, and its impact is seen solely on-site. Splash erosion may play a vital role in release of soil organic carbon (C).

(ii) *Sheet Erosion*

Soil is removed evenly in a thin layer by running water from the entire sloping land surface area. Raindrop splash erosion is the main cause for the sheet erosion. Dropping of raindrops causes the detachment of soil particles and increases sedimentation which reduces the infiltration rate through closing the soil apertures.

Fig. 2 Different types of water erosion. (Source: McCauley and Jones 2005; Hegde 2010)

(iii) *Rill Erosion*

Runoff water flowing along the slopes and loaded with soil materials form small finger-like channels known as rill erosion. It is an advanced form of soil loss through sheet erosion. It is an intermediate stage among sheet and gully erosion. It rarely occurred in the cultivable agricultural lands. An undulating land surface is the main responsible cause for rill erosion.

(iv) *Inter-rill Erosion*

It is a main element of highland destruction. Soil particles were detached and splash them into narrow overland courses through exposing soil surface by striking raindrops. Approximately, it is relative to the square of rainfall intensity. Flow of sediment into the rill channels is usually affected by the slope, cover and surface roughness.

(v) *Gully Erosion*

As the concentrated runoff volume increases and gets more velocity on sloppy areas, it broadens the rill and forms gullies. Often it forms along the bullock cart tracks or hideaways of animals. Gullies result in ravines in an advanced stage, occasionally which are 3–15 m deep. In India, ravine covers about 6 million acres area. Gullies can be classified on the basis of size, depth and drainage area. It occurs when rills continue to extend in width, depth and length and become more serious. It is more likely on steeper slopes and cannot be smoothened by normal tillage operations. Though the soil losses from gullies are not as serious as compared to sheet erosion, gullies are more conspicuous than the other types of erosion. Gullies can be classified on the basis of size, depth and drainage area.

(a) *U-shaped gullies:* U-shaped gullies are usually formed in alluvial valleys where both the surface and subsurface soils are easily eroded.
(b) *V-shaped gullies*: V-shaped gullies are formed in those areas where subsoils are more resistant than the topsoil. This is the most common type of gully shape.

(vi) *Tunnel Erosion*

Removal of subsoil through running water and the surface soil is remained intact. Tunnelling is occurred at the places where the permeability is varied within soil profile for water. Sheet erosion is a promoter for tunnel formation and is very difficult to identify during early stages. Compact and hard surface soil, and clayey subsoil may be stable in dry conditions but liable to erosion in wet condition. After widening and deepening of the tunnels, it forms large gullies and damages to the productive croplands.

(vii) *Slip Erosion or Landslip Erosion*

Down movement of mass of earth, debris or rock from sloppy lands due to the action of biotic and abiotic factors are known as slip erosion. Big masses of soil and rock body slip down which damages the productive field. Its impact varies along with agroclimatic zones of India.

(viii) *Stream Bank Erosion*

Streams and rivers change their flow direction by cutting one bank and depositing silt material on the other bank. Damage due to stream bank erosion is very much enhanced during flash floods. Within the last 220 years, Koshi River in Bihar changed its course westward by 120 km (Ghosh and Mukhopadhyay 2012). Stream bank erosion is the scouring of soil material from the stream bed and cutting of stream bank by the force of flowing water. Stream and gully erosion are more or less similar. Primarily, stream erosion occurs at the lower end water tributaries/streams having relatively flat slope and continuous flow of water. It is affected by the direction and velocity of flow, width and depth of channel.

(ix) *Water Falls*

Water falling vertically from high elevated place where the water is in free fall condition known as water falls. A stream of water falls over a rocky ledge into a plummet puddle. They are also known as torrents. The wearing soil material away from the land surface causes erosion problem through water falls.

(x) *Seashore (Coastal) Erosion*

Sea level is continuously increasing due to the global climate change. So, the seaside areas are alarming for natural disasters like tsunami. The strong water waves raised due to such natural hazards badly erode seaside areas. Erosion rates at seashore may likely to increase in the future. However, possibly 80–85% of the world's coastlines are retreating but the developing activities like construction of ports, destruction of mangroves, beach mining, river bed mining and sea bed disturbances due to tsunami, etc. are the responsible factors for seashore erosion (Hegde 2010).

(xi) *Ravine Formation*

Ravine area is a web of deep and narrow gullies with hasty sides. Continuous non-judicious use of the land represents a severe erosion hazard which results from enlargement of rills. It consists of a set of gullies which flows parallel to each other and is continually linked with river systems. Abrupt changes in elevation between the river bed and the adjoining land, deep and porous soil strata with high erodibility, scanty vegetative cover and back flow of river water during recession period result into severe bank erosion which further leads to ravine formation.

2.4 Wind Erosion (Loss of Topsoil Through Wind)

The soil degradation caused due to high wind velocity which scrapes, carryout and deposits soil particles. It mainly depends upon soil type, climatic conditions, vegetation cover and wind speed. The wind erosion has different phases and processes (Santra et al. 2013; Pimentel 2006; Ajai et al. 2009; Venkateswarlu and Kar 1996; Dhakal et al. 2016).

2.4.1 Phases of Wind Erosion

(i) *Detachment:* When the force of wind increases against the soil particles and overcomes the force of gravity, then soil particles detached from the land surface. Detached particles of soil under moving condition may collide with each other particles.

(ii) *Transport:* Separated soil particles from land surface became ready to transport by the wind, either through the air space or along the soil surface. The distance to be transported depends upon height of separated soil particles in air, duration of transport and speed of wind.
(iii) *Deposition:* When the wind velocity decreases, then the soil particles are deposited typically in furrows or vegetation areas. Along the boundary of fields, transported soil material gets deposited in ditches, live fencing rows or barriers such as windbreaks/shelterbelts. Very fine particles were travelled thousands of miles and then deposited on vegetation parts, other constructed buildings or in ditches.

2.4.2 Wind Erosion Processes

(i) *Surface Creep:* The large particles (having diameter of 0.5–2 mm in size) spun on the soil surface dislodging other particles. It happens in case of larger particles which travels only a few metres.
(ii) *Saltation:* Soil particles of middle size (having diameter of 0.05–0.5 mm) are light enough to be lifted from the soil surface, but are not suspended, and cause saltation. These particles move through a series of low bounces over the surface, forming scratches on the soil surface (Fig. 3).
(iii) *Suspension:* Particles having diameter less than 0.1 mm (tiny particles) can be lifted into the air and create dust storms. They include very fine sand grains, clay particles and organic matter (OM). The soil particles of 0.05–0.1 mm size may be dropped within 1–2 km from the site. The particles having size of 0.01 mm can move hundreds of kilometres and 0.001 mm-sized particles may travel thousands of kilometres.

3 Causes of Soil Erosion

Generally, in natural soil erosion, the erosion takes away soil material at approximately the same rate as soil is formed. When the loss of soil takes place at higher rate than its formation then the soil erosion rate is accelerated which poses danger

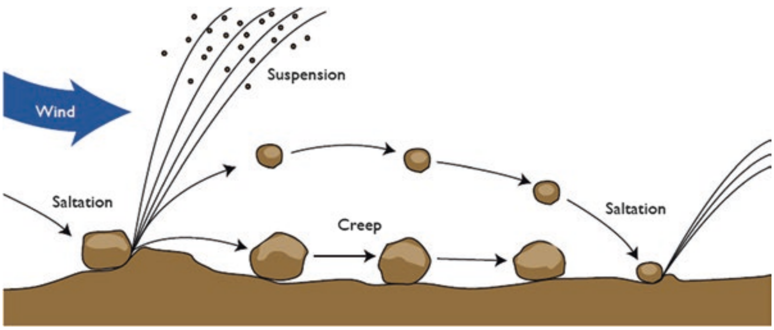

Fig. 3 Wind erosion processes. (Source: McCauley and Jones 2005)

for loss of soil and water resources. The acceleration in rate of soil erosion is caused due to the human imprudent actions like deforestation, overgrazing, forest fires, mining, injudicious cropping patterns, cultivation along the land slope and faulty methods of irrigation and unsafe land utilization pattern which is subjected to the action of rain and wind that accelerates soil erosion. Due to high rate of soil erosion, OM and plant nutrients are removed from the fertile topsoil and thus lowering crop productivity.

Factors Influencing Water Erosion

Universal Soil Loss Equation (USLE) involves the possible factors which cause soil erosion. The USLE was given by Wischmeier and Smith (1978).

$$A = R \times K \times L \times S \times C \times P$$

Where:

A = Mean annual soil loss (metric tonnes hectare^{-1} year^{-1})
R = Rainfall and runoff factor or rainfall erosivity factor (mega joules millimetre hectare^{-1} hour^{-1} year^{-1})
K = Soil erodibility factor (metric tonnes hectare hour megajoules^{-1} hectare^{-1} millimetre^{-1})
L = Slope-length factor (unitless)
S = Slope-steepness factor (unitless)
C = Cover and management factor (unitless)
P = Support practice factor (unitless)

Among these factors enlisted above, the vegetation and to some extent soil can be controlled for reducing the rate of soil erosion. Climatic and topographic factors, except slope length, are not be controlled and managed by human being to reduce soil erosion. The quantity of soil loss through erosion is therefore a function of energy involved in the running water or raindrops causing soil loss and the capacity of soil to withstand the impact of causative factors. Thus, in case of mathematics, soil loss is a function of erosivity of raindrops and erodibility of the soil.

$$\text{Erosion} = f\left(\text{Erosivity}, \text{Erodibility}\right)$$

Erosivity: The potential ability of precipitation to cause erosion and for a given soil condition.

Erodibility: Vulnerability or susceptibility to remove the soil material from soil surface is known as erodibility. Predominantly, it depends on the bio-physico-chemical characteristics of the soil. Moreover, it depends on the soil treatment (land management and crop management treatments) given for its specific use. Land management practices may involve contour farming, bunding, terracing, etc., while crop management practices on arable lands may include the kind of crop, the fertilizer treatment, harvesting and others.

4 Indicators of Soil Erosion

Verdict of an evidence of soil erosion in the field is the first step of soil and water conservation (SWC). There are some indicators that can be used for recognizing soil erosion (USDA–NRCS 2001):

- Bare soil
- Exposed roots of vegetation
- Surface soil crusts
- Increased tendency of runoff water to flow together into a network of connected channels
- Deposition of soil and debris at the point of slope change
- Decreased thickness of topsoil
- Opens the soil subsurface
- Observable rills or gullies
- Silt-clouded water or sediment deposits in surface water bodies and irrigation canals
- Poor plant growth

5 Impact of Soil Loss

Soil loss by the action of water and wind is the main problem; it diminishes the productive efficiency of all ecosystems (Meena et al. 2017; Bhattacharyya et al. 2015; Lal and Mishra 2015; Pimentel and Burgess 2013; Tandon 2007; Verma et al. 2015). The detailed impacts of soil erosion on terrestrial ecosystems are given below:

- *Loss of Fertile Topsoil:* This is the biggest impact of soil erosion, because this can cause serious harm to farmer's cultivation practices in the field through lowering the productivity of soil.
- *Soil Compaction:* Aeration in the subsoil lowers down due to compaction by action of abiotic and biotic factors. It reduces the rate of water infiltration to the deeper levels. It accelerates the rate of runoff, which upsurges the hazard of serious erosion and loss of crop productivity.
- *Poor Drainage:* Occasionally, more compaction with sand can lead to formation of hard surface layer; it restricts the water infiltration to deeper layers.
- *Less Water Availability:* All floras require sufficient amount of water for their growth and development, so that the water is most vital factor for productivity of all terrestrial ecosystems. Infiltration rate of water is reduced due to high rate of soil erosion. It creates drought conditions.
- *Loss of Nutrients:* Runoff carries away available nutrients from the soil. This is the fact that the concentration of nutrients is comparatively high in sediment and runoff water. Eroded fertile soil of 5.3 billion tonnes through runoff removes about 8 million tonnes of plant nutrients.

- *Depletion of SOM:* Decaying and decomposition of plant debris like leaves, branches, twigs and flowers reduce the SOM significantly which increases the erosion losses. The depletion of an OM results in lowering the productivity of different ecosystems (Sanchez et al. 1989).
- Frequently occurrence of drought and flood conditions.
- Less availability of water resources from seasonal as well as year-round flowing rivers.
- *Soil Acidity Levels:* SOM declines due to the erosion processes; it leads to rise in acidity of soil. Such condition restricts the availability of nutrients and ultimately brought disturbances in the soil heath.
- *Reducing Soil Depth:* Plant growth mainly depends on the root system. Strong and healthy root system means the proper growth and development of plant. Growing root system of plants needs adequate soil depth. Soil loss through any kind of force may reduce soil depth up to 1cm; it resulted in stunted plant growth.
- *Plant Reproduction:* In case of cultivable lands, new seeds and seedlings are buried and destroyed due to running water and wind force. High wind force at the time of flowering and fruiting stage of plants brakes the branches; it impacts future plant production.
- *Loss of Biodiversity:* Total organism present in a particular place is known as their diversity. An availability of SOM in any kind of ecosystem affects soil biodiversity. Biomass and biological activities in the soil may also diminish through erosion losses.
- Deforestation, clearing of vegetation and losses to the habitats.
- Groundwater level is continuously reducing due to high rate of erosion and increase in the use of groundwater by digging tube wells.
- *Sedimentation of Water Bodies:* Deposition of sediment in water bodies may reduce their capacity and increases the risk of overflow. Such processes are leading to scarcity of available water in off monsoon season.
- *Water Pollution:* Runoff water from agriculture fields comprises concentration of fertilizer, weedicide and pesticide; it pollutes water bodies badly. It also contaminates water bodies and harms aquatic flora and fauna.
- Adversely affect the economy and culture.

6 Problems Faced by the World, India and Madhya Pradesh

(i) *Increase in Groundwater Utilization*

In the year 1950, only 30% required irrigation water were derived from groundwater sources (Fig. 4), whereas in 2009, it increased up to 60%. It means that the use of groundwater increased two times in 59 years (Ministry of Agriculture 2015). In the 1980s, groundwater and surface water were equally used for agriculture practises. After the 1960s, the rate of runoff was high. It happened due to the deforestation activities and loss of SOM, decreasing availability of surface water.

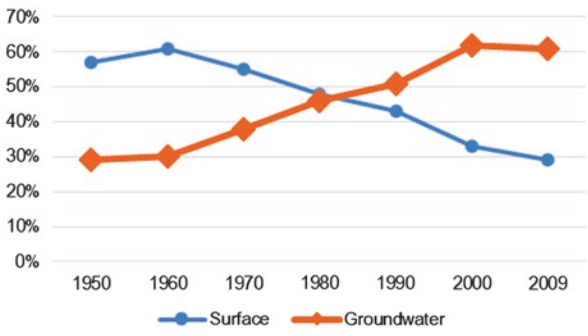

Fig. 4 Increase in groundwater utilization for irrigation. (Ministry of Agriculture 2015)

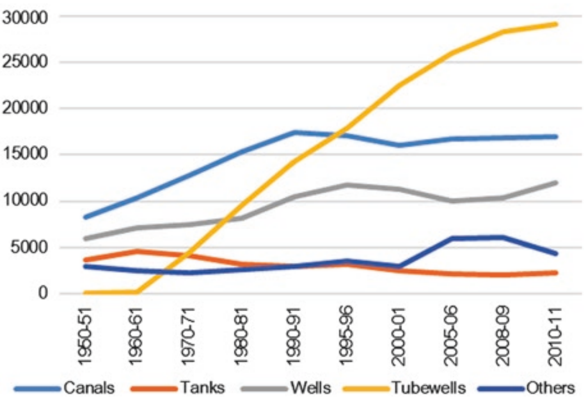

Fig. 5 Tube wells increasingly being the main source of irrigation (Irrigated area is in '000 hectares). (Ministry of Agriculture 2015)

Wells and tube wells were used for pumping the groundwater. After 1960–1961, the drilling of tube wells increased continuously. Up to 2010–2011, tube well becomes a main source of irrigation (Fig. 5).

(ii) *Groundwater-Level Fluctuations*

The groundwater level examined in January 2016 when compared with mean groundwater level of the last decade (2006–2015) reflected that the 9268 (65%) open wells showed lowering of the water level, in 44% wells water level lowered by 0–2 m, 13% wells by 2–4 m and remaining 9% wells by>4 m (CGWB 2016). Lowering in water level by>4 m was prominent in Madhya Pradesh, Gujarat, Haryana, Andhra Pradesh, Chhattisgarh, Delhi, Karnataka, Punjab, Maharashtra, Rajasthan, Telangana and West Bengal.

The 4904 (about 35% of total sampled) wells improve water level. Out of 4904 wells, 28% wells showed upsurge in groundwater level by <2 m, 4% wells showed rise in water level by 2–4 m and 2% wells showed increase groundwater level by>4 m. Improvement in groundwater level by>4 m was observed in Gujarat, Himachal Pradesh, Rajasthan and Tamil Nadu states of India (CGWB 2016).

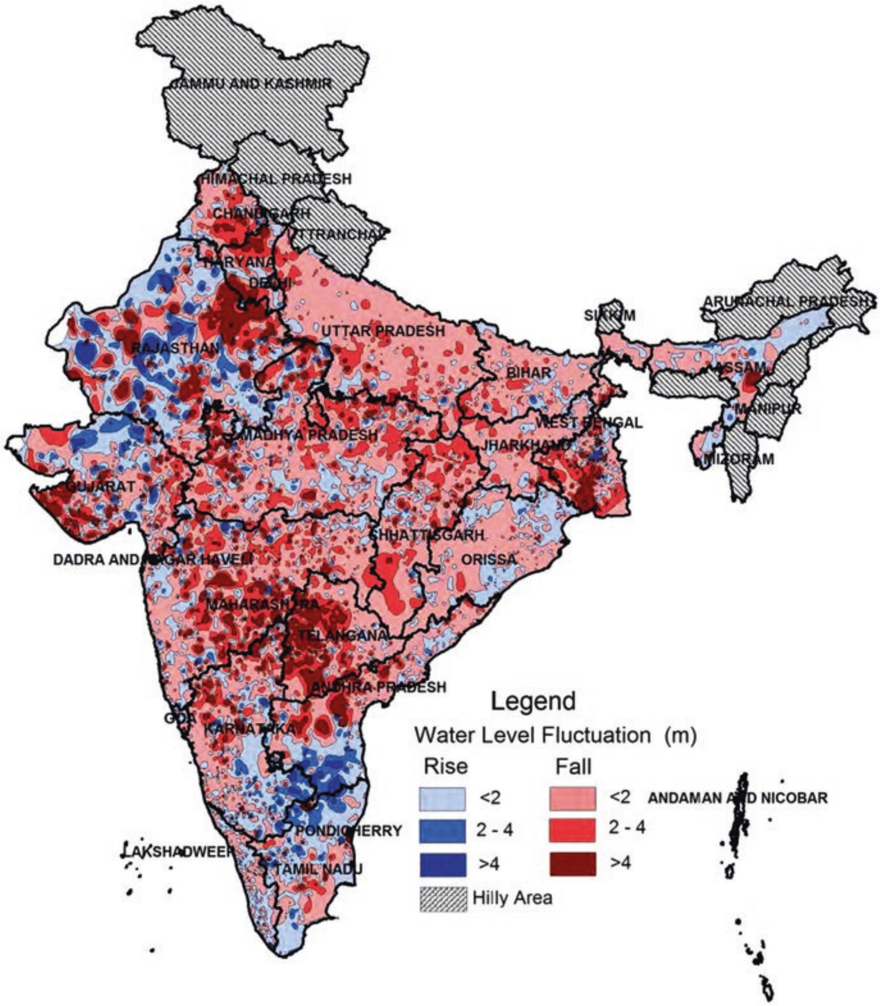

Fig. 6 Water-level fluctuations (decadal mean 2006–2015 vs 2016). (Source: CGWB 2016)

The map of groundwater-level fluctuations in India for the last decade (2006–2015) as compared with January 2016 is given in Fig. 6, whereas distribution of variability ranges is shown in Figs. 7 and 8.

(iii) *Availability of Water*

The availability of water is a major controlling factor for productivity in all kinds of terrestrial ecosystems because plants require huge amount of water for growth and development. At the time of high rate of soil erosion due to erratic rainfall, runoff significantly decreases infiltration rate, and less water becomes available for growing vegetation. For example, 1 ha of rice/paddy (*Oryza sativa*) needs 3390 m^3/ha irrigation water in eastern Uttar Pradesh, 3715 m^3/ha in central,

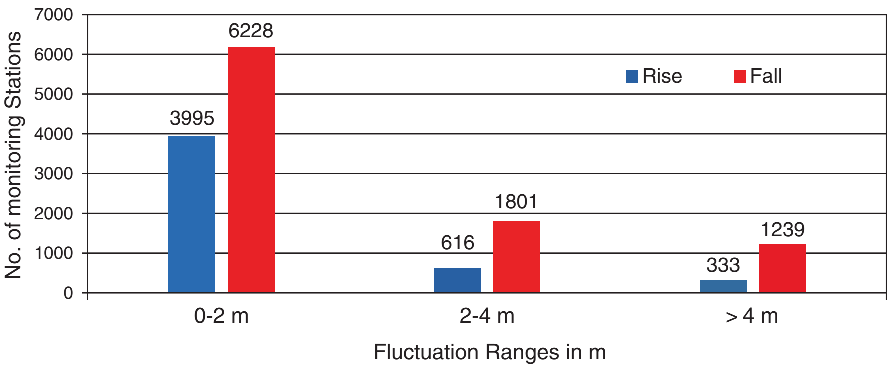

Fig. 7 Decadal water-level fluctuation ranges (decadal mean 2006–2015 vs 2016). (Source: CGWB 2016)

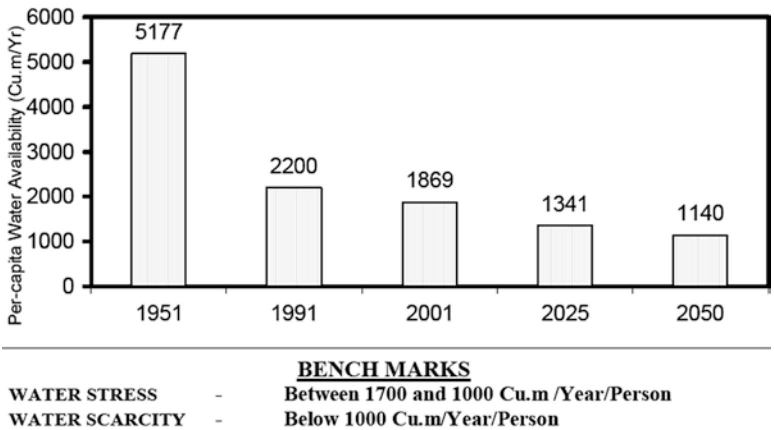

Fig. 8 Per capita water availability in India. (Source: Planning Commission 2007)

5316 m^3/ha in Bundelkhand and 3906 in western Uttar Pradesh (Kumari et al. 2017), whereas 12587–13710 m^3/ha water required for rice irrigation in Punjab (Kaur et al. 2010).

(iv) *Loss of Nutrient*

Plant macronutrients such as nitrogen (N), phosphorus, potassium, calcium, etc. were carried out along with runoff water which revealed negative effects on agricultural productivity (Singh et al. 2014; Meena et al. 2017). Young (1990) reported high nutrient concentration in soils collected from runoff loads as compared to the soil of cultivable fields. Annually, 16 tonnes/hectare soil was lost which exceeds the permissible limit of 12 tonnes/hectare. Around 140 Mha degraded land, 6000 MT of fertile soils was lost which causes loss of 5.5 MT of N, phosphorus and potassium (NBSS&LUP 2004; Lal and Mishra 2015; Meena et al. 2017). Santra et al. (2013) reported 45.9 kg C ha^{-1} and 4.3 kg N ha^{-1} content in eroded soils during the month of July.

(v) *SOM*

The fertile soils have 4–5% of OM as compared to total topsoil. SOM is very important, because it improves soil bio-physico-chemical properties. Allison (1973) reported that the SOM contains an approximately 95% of N and 25–50% of phosphorus. Losses of soil organic matter near soil surface due to decomposition and decay of leaf litter/crop residues may leads to soil erosion. Higher forces of wind and water erode soil and the fine organic particles which leave larger soil particles on the soil surface. Lal and Stewart (1990) reported that the soil material removed either by water or wind erosion processes has 1.3- to 5-fold higher OM than the soil left behind.

(vi) *Soil Depth*

An adequate depth of soil improves growth and development of plants. Barriers like boulders in the subsoil impart growth of root systems and stunted plant growth. The soil biota, like earthworms, also require a suitable soil depth for their activities. When the soil erosion significantly reduces soil depth from 30 cm for deep soils to even less than 1 cm for thin soils, plant root space can be minimized, and the plants could be stunted.

(vii) *Impact on Crop Productivity*

Undesirable changes in biotic and abiotic factors deteriorate the crop productivity. The abiotic factors are crucial because they can be managed in lesser extent, whereas biotic factors can be managed for larger extent. In case of abiotic factors, soil loss by the action of water and wind plays an important role in deteriorating crop productivity. Systematic efforts were carried out by Sharda et al. (2010) to evaluate the effect of water erosion on crop productivity at central soil and water conservation research and training institute, Dehradun. They reported that the water erosion imparts the annual production by 13.4 Mt in 2008–2009 at national level. Crop-wise losses are depicted in Fig. 9. Degree of harshness of water

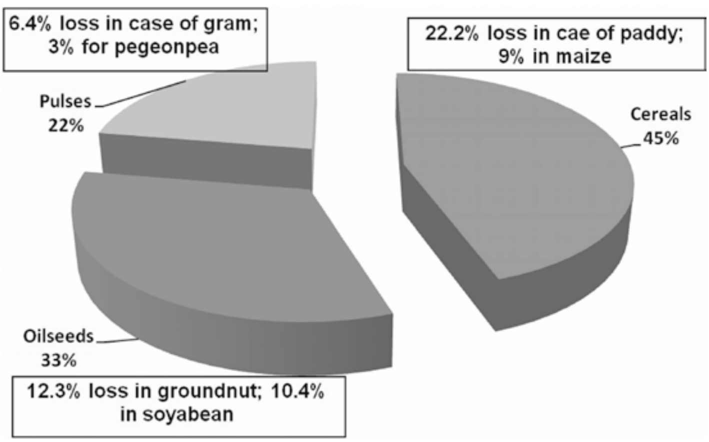

Fig. 9 Losses for cereal, oilseed and pulse crops due to water erosion. (Mishra et al. 2011)

erosion is very much related to the loss of agricultural productivity. The red soils are more susceptible for reducing crop productivity because of the loss of fertile topsoil.

7 Soil and Water Degradation Scenario from Agricultural Perspectives

(i) *Extent of Land Degradation in India*

Soil health erosion falls off the ecosystem functions. It effects on services such as food production, hydrological and nutrient cycling. "The Global Assessment of Soil Degradation" defines the soil degradation as "a human-induced phenomenon" and described the deterioration of soil quality and loss of one or more soil functions partially or entirely. The status of soil degradation is given below in Table 1. Around 86 Mha productive lands are affected by loss of fertile soil (Anonymous 2010a). According to Indian Institute of SWC, CAZRI (Central Arid Zone Research Institute), Central Soil Salinity Research Institute, National Bureau of Soil Survey and Land Utilisation Planning (NBSS&LUP) and NRSA, the total degraded land is 120.72 Mha. According to NBSS&LUP-ICAR (2005), 146.8 Mha areas were affected by different kinds of land degradation. Out of that 93.7 Mha land were affected by water erosion, 9.5 by wind erosion and 43.6 by other means (Table 2). Madhya Pradesh + Chhattisgarh accounts 26.2 Mha area degraded due to water erosion, which is highest in comparison with remaining states. It is followed by Uttar Pradesh + Uttarakhand (15.3 Mha), Andhra Pradesh+ Telangana (15.0 Mha), Maharashtra (13.1 Mha) and Rajasthan (11.4 Mha).

Such extent of degraded land affects on crop productivity and food security. So, there is an urgent need to think about the losses due to soil and water erosion which creates devastating impacts on Indian agriculture. Therefore, major stress should be given upon the conservation of soil and water under Indian agriculture system.

(ii) *Causes of Soil Degradation*

The process of soil degradation includes natural and artificial mode which are described below:

Table 1 Status of degraded lands in India (Anonymous 2010a)

Particulars	Land area (Mha)	Open forest (<40% canopy)(Mha)
Water erosion (>10 t/ha/year)	73.27	9.30
Wind erosion	12.40	–
Chemical degradation (salt/acid affected soils)	17.45	7.23
Physical degradation (mining, industrial waste and water logging)	1.07	–
Total	104.19	16.53
Grand total (arable land and open forest)	120.72	

Table 2 Statewise status of degraded land by water and wind erosion (NBSS&LUP-ICAR 2005)

Sl. No.	State/Union territory	Water erosion (area Mha)	Wind erosion (Area Mha)	Degraded area (total area Mha)	% of degraded area to total geographical area
1.	Andhra Pradesh + Telangana	11.15	–	15.0	54.5
2.	Goa	0.1	–	0.2	43.9
3.	Karnataka	5.8	–	7.6	39.8
4.	Kerala	0.1	–	2.6	67.1
5.	Tamil Nadu	4.9	–	5.3	41.0
6.	Manipur	0.1	–	1.9	42.6
7.	Mizoram	0.1	–	1.9	89.2
8.	Meghalaya	0.1	–	1.2	53.9
9.	Assam	0.7	–	2.2	28.2
10.	Arunachal Pradesh	2.4	–	4.6	53.8
11.	Nagaland	0.4	–	1.0	60.0
12.	Sikkim	0.2	–	0.3	33.0
13.	Tripura	0.1	–	0.6	59.9
14.	Himachal Pradesh	2.8	–	4.2	75.0
15.	Jammu and Kashmir	5.5	0.1	7.0	31.6
16.	Uttar Pradesh + Uttarakhand	11.4	0.2	15.3	52.0
17.	Delhi	0.1	–	0.1	55.4
18.	Haryana	0.3	0.5	1.5	33.2
19.	Punjab	0.4	0.3	1.3	25.4
20.	Bihar + Jharkhand	3.0	–	6.3	36.1
21.	West Bengal	1.2	–	2.8	31.0
22.	Union Territory	0.2	–	0.2	24.8
23.	Gujarat	5.2	0.4	8.1	41.5
24.	Rajasthan	3.2	6.7	11.4	33.2
25.	Madhya Pradesh + Chhattisgarh	17.9	–	26.2	59.1
26.	Maharashtra	11.2	–	13.1	42.4
27.	Orissa	5.0	–	6.1	39.3
Total		**93.7**	**9.5**	**146.8**	**–**

Natural causes

- Increasing rate of soil and water erosion
- Steep slopes
- Poor soil structure
- High rainfall intensity
- Changing climatic conditions

Artificial causes

- Farming without applying adequate conservation measures for tackling the land degradation problems.
- Overgrazing on pasture lands alone accounts for 36% of land degradation across the globe.
- Degrading soil physico-chemical properties due to non-judicious use of fertilizer without maintaining SOM.
- Soil salinization and excessive pumping of groundwater for irrigation and other uses in agricultural practices.
- Changes in river flow channel and sedimentation in water bodies.
- Clearing of natural flora for agriculture and non-agriculture uses.

8 Conservation Measures

8.1 Biological Measures

8.1.1 Forestry Measures

(i) *Afforestation and Reforestation*

Artificial growing of forest tree species or tree stands in the areas where there was no previous tree cover is known as afforestation, whereas reforestation is the artificial or natural restocking of existing forests and woodlands after harvesting/cutting (Schuck et al. 2002). Wolosin (2017) focused on the India's set targets for afforestation and restoration of forest ecosystems (Table 3). The perennial tree species, shrub, bamboo and palm species have potential for SWC (Sarvade et al. 2014a; Jahanifar et al. 2017; Yadav et al. 2018). Bonell et al. (2010) studied the influence of hydraulic conductivity of soil on tree growth and different uses of forest in Western Ghats, India, and reported that hydraulic conductivity near soil surface was restored beneath the *Acacia auriculiformis* (Earleaf acacia) plantations under red and lateritic soils with quite low rate as compared to the less disturbed forests. Huang et al. (2003) reported that the afforestation through deciduous tree species and natural grasses reduces the volume and peak flow of runoff in the treated watershed of the Loess Plateau, China.

Table 3 Afforestation and forest restoration targets of India (Wolosin 2017)

Particular	Afforestation and reforestation	Rehabilitation and improved tree cover	Time period
National Forest Policy	Bring 33% of India's land under forest cover		Not time bound
National Afforestation Programme	3 Mha total 600,000 ha year^{-1}	~20 Mha total ~4 Mha year^{-1}	2002–2007
Green India Mission	5 Mha total 500,000 ha year^{-1}	5 Mha total 500,000 ha year^{-1}	2010–2020
Low C strategy	1.7 Mha year^{-1}	2 Mha year^{-1}	By 2023

Afforestation and reforestation practices help to prevent deforestation and also work for achieving goal of National Forest Policy, 1988. Policy aims towards bringing 33% area under forest (20% in plains and 60% in hilly and mountainous areas) cover. For the fruitful and workable outcomes for achieving forest policy goals, new plant species would be grown only where the natural regeneration in first phase has been completed successfully (Sreedevi et al. 2006).

(ii) *Natural Forests*

The forest cover improves microclimatic conditions to help the reclamation of cultivable and uncultivable waste lands and natural resource conservation (Ong and Swallow 2003). The perennial tree species in the upper, shrub species in middle and grass species in lower story may prepare a netlike structure for reducing speed of falling raindrop which helps to decrease in splash erosion and other types of erosions also. Sharma and Rai (2004) studied the stemflow, carriage of sediment and C from the Himalayan forest and other systems, and they reported that the volume of total rainfall was divided into 77.71% throughfall, 9.92% stemflow and 11.40% diverted through plant canopy (Table 4). They also reported that the 45% of the rain fall water was collected as leachate, whereas 55% from surface runoff. This study concluded that the vegetation cover reduces the runoff losses and helps in SWC.

8.1.2 Agroforestry Measures

Agroforestry is a cultivation of agriculture, tree species, bamboo, shrubs, palms and/or livestock simultaneously or sequentially on same piece of managed land (Jhariya et al. 2015; Singh and Jhariya 2016). Bene et al. (1977) defined the agroforestry as sustainable land use system that upsurges total production; it combines agricultural crops and forest plants and/or animals simultaneously or sequentially and applies management practices that are compatible with the cultural patterns of local population.

Sarvade et al. (2014a) reported the potential of agroforestry for improving soil health and increasing crop productivity. The processes such as leaf litter addition

Table 4 Throughfall and stemflow affected by different land use systems temperate and subtropical region of India

	Regions with land use systems				
	Temperate			Subtropical	
Particulars	Temperate natural dense forest	Temperate natural open forest	Cardamom-based agroforestry system	Subtropical natural open forest	Mandarin-based agroforestry system
Throughfall (mm)	2355 (96)	974 (48)	1633 (54)	721 (26)	746 (50)
Stemflow (mm)	297 (19)	441 (26)	162 (13)	32 (7)	68 (5)
Canopy interception (mm)	341 (76)	1577 (22)	1197 (67)	541 (19)	481 (55)
Floor leachate (mm)	1195 (105)	1226 (71)	1215(68)	290 (36)	573 (26)
Floor interception (mm)	1456 (31)	189 (49)	580 (135)	464 (54)	241 (29)

may act as a protective layer to maintain soil bio-physico-chemical properties to increase soil moisture retention and efficient nutrient cycling (Sharma et al. 2007; Gupta et al. 2015; Meena and Yadav 2015; Jhariya 2017).

Planting of nitrogen-fixing tree species (NFTs) keeping wide spacing helps to improve soil physico-chemical properties and productivity of wheat (*Triticum aestivum*) in Tarai region of Uttarakhand (Sarvade et al. 2014b, c). The different agroforestry practices help to reduce the loss of 20% N by reducing 1 to 10% soil erosion (Udawatta et al. 2002). The agroforestry systems such as large cardamom (*Amomum subulatum*) and mandarin orange (*Citrus reticulata*)-based agri-horticultural systems were the best examples reported from the Sikkim state of N-E region of India for conservation of natural resources and development of fragile mountain ecosystems (Mishra and Rai 2013).

(i) *Agri-Silviculture*

Growing of agricultural crops as a principal component with multipurpose trees (MPTs) as a secondary component on same managed land unit in some temporal and special sequence. Perennial tree species has long tap root system which helps in binding of soil at root zone and increases the infiltration rate with reducing runoff losses. Growing of NFT species helps to improve soil fertility especially N content of the soil is improved through litter addition and further decomposition and release of essential plant nutrients (Sarvade et al. 2014a; Toppo et al. 2016; Jhariya et al. 2018b). This system is widely used for reclamation of degraded lands. In this context, continued growth of trees on alkali soils ameliorates these soils through decreasing soil pH and electrical conductivity, enhanced OM content and enhanced fertility of soil. Study carried out by Singh (2007a, b) at Dehradun revealed that the growing of *Eucalyptus hybrid* (flooded gum) and *Leucaena leucocephala* (subabool) in this system considerably reduces runoff and soil loss (Table 5). He also conveyed that the growing of grasses with eucalyptus was more effective for controlling runoff and soil losses as compared to subabool+ grass.

This practice is common in the western Himalayan region to cultivate wheat, peas (*Pisum sativum*), potato (*Solanum tuberosum*), cauliflower (*Brassica oleracea*

Table 5 Effect of different land use systems on average runoff and soil loss (Singh 2007a, b)

Land use	Runoff (%)	Loss of soil (MT/ha)
Chrysopogon fulvus (Guria grass)	12.7	8.65
Sole maize (*Zea mays*) crop	27.5	28.27
Maize with subabool	21.4	17.83
Maize with eucalyptus	20.8	13.51
Subabool with grass	17.6	10.51
Sole subabool	2.4	1.74
Eucalyptus with grass	6.3	3.52
Sole eucalyptus	2.1	1.20
Cultivable fallow	38.2	56.58

var. botrytis), mustard (*Brassica juncea*), etc. during winter and maize, tomato (*Solanum lycopersicum*), chillies (*Capsicum annuum*), etc. during the summer season on the permanent terraces prepared across the hill slopes. Multipurpose tree species, viz. *Grewia optiva* (buel), *Celtis australis* (Khirak), *Bauhinia variegata* (Kachnar), *Albizia chinensis* (Ohi), *Toona ciliata* (Toon), *Morus alba* (Toot), *Ulmus laevigata* (Marn elm), etc. are intentionally left or grown on the bunds of terraces. It is a dominant system in submontane and mid-hills subhumid zone of Himachal Pradesh. The MPTs generally follow a random or irregular geometry, except in the case of plantations and orchards, and serve multiple objectives like green manure, fodder, fuel, fruits, nuts, small timber, etc. Competition however is a major constraint in this respect, and roots of many species grown on the same piece of land frequently intermingled, and often this overlap of the roots can be extensive, especially in older stands (Jamaludheen et al. 1997; Divakara et al. 2001).

(ii) *Agri-Horticulture*

Fruit tree species can be successfully planted on degraded and low fertile lands with some restoration measures. The humps and gully beds of ravines are suitable for growing fruit tree species. In gully beds, MPTs like lemon (*Citrus limon*), mango (*Mangifera indica*), ber (*Ziziphus mauritiana*) and aonla (*Phyllanthus emblica*) are planted at required spacing in agriculture fields. Line to line and row to row spacing varied from 2 m × 2 m to 8 m × 8 m as per growing habit of species. The wider spacing is adopted for tree planting in ravine land as compared to levelled fertile lands. During summer, pits were dug out with the size of 1 m × 1 m × 1 m and exposed to bright sun. Planting of tree species should be carried out at onset of monsoons. Palatable grasses were planted in interspaces of tree rows. It is best way to utilize interspace and reduce soil erosion. Small water resources should be generated for life-saving irrigation to the fruit tree species.

(iii) *Silvi-horti-pasture or Horti-agricultural Model*

In general, fruit trees are less tolerant to sodic soils as compared to the most of perennial forest species. Then the cultivation of fruit tree may be recommended in soils having pH < 9.5. Fruit species like *Carissa carandas* (karonda), ber, aonla, *Syzygium cumini* (jamun) and *Psidium guajava* (guava) can be successfully grown on sodic soils. Isabgol *(Plantago ovata*) and *Matricaria chamomilla* (chamomilla) can be grown as intercrops between horticultural tree species on the soils having pH<9.5.

(iv) *Sequential Agroforestry*

Instead of growing multipurpose tree species and agriculture crops simultaneously, they are grown in sequence. It is followed by many peoples for improving the soil fertility status, which is exhausted by incessant monocropping. Short-rotation, fast-growing and NFT, i.e. *Sesbania sesban* (Egyptian riverhemp), subabool, arhar (*Cajanus cajan*), etc. are grown on fallow land for 4–5 years and then cut for multiple uses, and then land is utilized for agriculture.

Table 6 Salient features of shelterbelt (Anonymous 2016)

Height of tree (m)	Length of break (m)	Increase in length of break	Area protected (m^2)	Increase in area protected
15	30	–	14	–
15	60	2 times	56	4 times
15	360	6 times	2016	36 times
15	792	2.2 times	9757	4.84 times

(v) *Windbreaks and Shelterbelts*

These are vegetation barriers established at right angle to the wind direction with an aim to decrease wind speed, evaporation and soil erosion. It gives an assistance to guard the crops and controls the drifting of sand particles. Planting of trees, shrubs and other vegetative barriers around agriculture farm and farm buildings to protect against the action of wind. Similar to windbreaks such as planting on larger scale and designed to protect a number of fields are known as shelterbelts. The salient features of shelterbelt are depicted in Table 6.

Anonymous (2016) reported the following important plant species such as babul (*Acacia nilotica*), siris (*Albizia lebbeck*), neem (*Azadirachta indica*), shisham (*Dalbergia sissoo*), khejri (*Prosopis cineraria*) in central row, kumat (*Acacia senegal*), runjha (*Acacia leucophloea*), casia (*Cassia siamea*), Israeli babul (*Acacia tortilis*), vilayati babul (*Prosopis juliflora*), farash (*Tamarix aphylla*) in flank rows and baonli (*Acacia jacquemontii*), *Agave* sp. (sisal), kair (*Capparis aphylla*), Phog (*Calligonum polygonoides*), Jerusalem Thorn (*Parkinsonia aculeata*), Pilujal (*Salvadora oleoides*), Bordi (*Ziziphus nummularia*) and Vilayati Kaulasi (*Dichrostachys glomerata*) for outer rows of windbreaks and shelterbelts for resource conservation.

Nuberg (1998) reviewed the impact of windbreaks and shelterbelts on temperate crops and concluded with very favourable effect in concern with soil, water conservation and increase in crop productivity. Odd number of tree rows was planted to protect crop field by checking the wind velocity, in the coastal and dry regions. Depending on the scale of hazard of wind erosion, recommendation was given to growing of five-row or three-row shelterbelts in triangle shape. *Acacia bivenosa* (two-nerved wattle), *Acacia ampliceps* (salt wattle), ber and phog are the suitable shrub species for flank rows of shelterbelt, whereas babul, Israeli babul, cassia and siris are the suitable tree species for central rows (Prasad and Mertia 2009; Mertia et al. 2006; Venkateswarlu and Kar 1996; Ram and Meena 2014).

(vi) *Alley Cropping*

This system widely used in hilly areas where the growing of agriculture crops is carried out on slopes and hedge of NFT, and shrubs are planted on contours. Distance between two hedge rows may be 4–5 m, and plant to plant distance within one row may be 25–40 cm. In this system, pruned plant material and crop residue are used as manure and mulch and may be used as a fodder for livestock. Leguminous tree species planted in hedge rows made successful system for SWC (Ogunlana et al.

2010). In hilly areas, alley cropping is one of the effective measures for control of soil erosion. Kidd and Pimentel (1992) studied alley cropping of subabool+maize crop in three rows at right angle to the slope (10–15%) and reported that the system can control loss of soil when the residues of maize (2000 kg) and the pruned material of subabool (2500 kg) were retained on the soil surface.

Pandey et al. (2001) conveyed high SOC and low total N in alley cropping as compared to the sole cropping. Study was carried out on alley cropping in rain-fed agroecosystems by Solaimalai et al. (2005) and comes with some interesting conclusions that alley cropping/hedge row intercropping serves safety against loss of nutrient through leaching, soil loss, mobilization of nutrients, cycling of nutrients and nutrient pumping from deep soil layers. Prabhakar et al. (2010) reported relative high awareness level (>87% farmers) is perceived in relation to concerns about agroforestry, alley cropping and social forestry, whereas knowledge of farm forestry, social forestry, agroforestry, alley cropping, silvi-horti-system, silvi-pasture system and agri-horti-system were fully adopted by >40% farmers for natural resource conservation.

(vii) *Grassland/Silvi-pasture System*

Planting of tree species under silvi-pasture and horti-pasture system medium, shallow and deep gullies can be reclaimed and utilized for agriculture. Sowing of grass seeds also supplies suitable safety to the different mechanical conservation structures established for treating the ravines. Suitable grass species may be selected as per the type of soil and availability of soil moisture. *Cenchrus ciliaris* (buffel grass), *Cenchrus setigerus* (birdwood grass), *Dichanthium annulatum* (marvel grass), *Panicum antidotale* (blue panicgrass), *Panicum maximum* (Guinea grass), *Brachiaria mutica* (para grass) and *Pennisetum purpureum* (elephant grass) are important grass species used in ravine restoration (Gupta et al. 2007) (Fig. 10).

Fig. 10 Silvi-pasture system

The most promising woody species for alkali lands are identified as-vilayati babul, babul, *Casuarina equisetifolia* (beach oak), *Terminalia arjuna* (arjun), *Tamarix articulata* (farash) and *Pongamia pinnata* (karanj). Salt tolerant and high amount of OM producing grass species such as Kallar grass (*Leptochloa fusca*), Rhodes grass (*Chloris gayana*), Para grass and alkali sacaton (*Sporobolus* spp.) can be grown with above listed trees. Vilayati babul and kallar grass growing in silvi-pasture have been recognized most auspicious for soil amelioration, firewood and forage production.

Palmarosa (*Cymbopogon martinii*) and lemon grass (*Cymbopogon flexuosus*) are aromatic grasses that can be successfully grown on moderate alkali soils (pH up to 9.2), whereas vetiver (*Vetiveria zizanioides*) bears both high pH and waterlogged condition without reducing significant yield (Dagar et al. 2004).

(viii) *Slopping Agricultural Land Technology (SALT)*

It is mainly a method of growing crops between the rows of N-fixing shrub and tree species (Fig. 11), i.e. *Gliricidia sepium* (Mexican lilac) and subabool (Watson and Laquihon 1985; Geddes 2007). As per specific needs, ICAR Research Complex for NEH region developed a three-tier SALT system for sloppy hills (agriculture in lower one-third bench terraced area, middle one-third for horti-pasture where grass species were grown on the contour bunds, and remained one-third area was utilized for agroforestry) with keeping some flexibility. Fallow period deteriorates the soil fertility and reduces crop productivity. Deterioration of soil fertility in fallow period is improved through growing of NFT species, which improves N availability to the next season crops. *Centrosema pubescens* (butterfly peas), Egyptian riverhemp, subabool, arhar, *Tephrosia*, *Mucuna*, *Pueraria*, *Indigofera*, *Crotalaria* and *Mimosa* are N-fixing species which can be successfully used to rejuvenate the soil fertility.

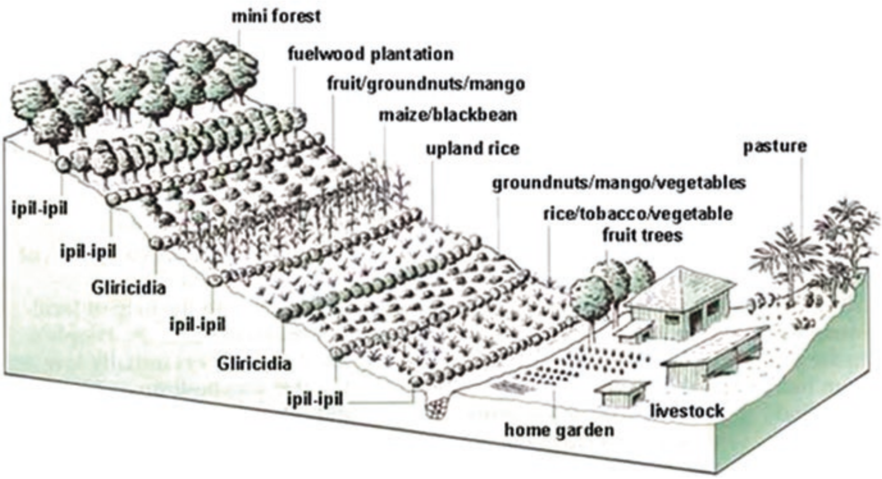

Fig. 11 Pictorial model of SALT. (Source: Mittleman 2012)

Advantages of SALT

It has good potentials over shifting cultivation and conventional terrace farming in upland areas of north-eastern region, India.

- It shelters the area from soil loss problems.
- It improves soil physico-chemical properties.
- It produces food crop sustainably in hilly upland areas.
- It is simple and easily adopted by the farmers.
- Culturally and socially, it is acceptable.
- Applicable for small and marginal farming communities of the areas.
- Technology is economically feasible and ecologically sound.
- It reduces the human pressure from the forest resources.

An efficiency of SALT on soil fertility of mid-hills in Nepal was assessed by Lamichhane (2013) and reported positive results of *Indigofera dosua* (Kathewat) and *Alnus nepalensis* (Nepal alder) on quantity of runoff water, loss of soil, crop production, retention of soil water and soil nutrients.

(ix) *Live Fencing*

The planting of multipurpose trees (i.e. Poplar, Willow, *Ficus*, *Boswellia*, *Erythrina*, *Lannea*, *Bombax*) was done through vegetative cuttings of usually 0.5–1.5 inches in diameter and 18–36 inches long. The side branches of cutting materials are neatly removed. Young shoots of 1–2 years old work best under this technique for resource conservation. Tree stems of large diameter have a greater mortality rate; however, it may be effective with the application of rooting hormones. These stakes create a netlike structure; it binds soil near the surface and reduces runoff rate and also helps in conserving soil moisture (Lewis 2000). It is suitable for repairing land slide areas where it is a minor problem.

Live fencing is also essential for protecting the treated ravine lands from biotic agents. It results in 70–120% increase in biomass of grasses, which reduces erosion problem. Gulley area of river Chambal was brought under good grass cover in 2–5 years. *Acacia caesia* (aila), *Acacia concinna* (Shikakai), sisal, *Agave americana* (Century plant), *Duranta repens* (golden dewdrop), *Erythrina variegata* (Indian coral tree), Mexican lilac, *Euphorbia spp*., *Jatropha spp*., *Pithecellobium dulce* (Manila tamarind) and *Vitex negundo* (chaste tree) are common plant species grown at close spacing of 0.2–0.5 m in live fencing of the home gardens, whereas, aila, sisal, *Borassus flabellifer* (palmyra palm), century plant, Indian coral tree, *Murraya koenigii* (curry leaf), *Jatropha curcas* (physic nut), *Ipomoea carnea* (bush morning glory), *Lantana camara* (lantana), Manila tamarind and *Randia malabarica* (cholakara) are the suitable species for live fencing around field crops in the northern part of the Eastern Ghat region (Andhra Pradesh, Orissa and Chhattisgarh) of India (Choudhury et al. 2004). Mathukia et al. (2016) reported multipurpose tree species like *Erythrina abyssinica* (red hot poker tree), Mexican lilac, *Sesbania grandiflora* (agati), *Euphorbia spp.* and *Acacia spp.* for live fencing in Gujarat. They also reported an importance of such MPTs for natural resource conservation.

8.1.3 Agricultural Measures

Soil conservation means protect the soil from erosion losses and dwindling soil fertility due to their acidification, salinization, intensive agricultural practices and some soil pollutants. Soil loss by water and wind is the greatest evil of agriculture and animal husbandry in India. Farmers applying soil and water conservation practices benefited more in terms of higher yield and conservation of natural resources than the farmers not practicing soil and water conservation.

(i) *Crop Rotation*

Use of agricultural practices based on sustainability is the most significant measure to conserve soil and water resources. Monocropping in many parts of India is one of the obstacles in conservation practices. It results in exhaustion of soil nutrients and degrades soil fertility. Rotation of growing crops is helpful to conserve soil fertility. It will provide enough time and also provide services to restore the lost nutrients during erosion and other causes of depletion of soil fertility. Legume crops add nitrates to the soil through atmospheric N fixation. Along with this, the plant residue incorporation in soil conserves soil and water resources and also improves soil health through their decomposition.

(ii) *Strip Cropping*

Crops were grown in alternate strips parallel to one another. Some strips may be kept unplanted. The harvesting of different agricultural crops carried out at different intervals. In this context, the complete area is not left bare throughout the year. The crops having tall height functioned as windbreaks. The strips are always parallel to the contour lines, which help in cumulative water absorption and slackening runoff losses.

(iii) *Contour Ploughing*

The fields were ploughed at right angles to the slope. After the ploughing, ridges and furrows are made across the soil slope. It disrupts the flow of runoff from the sloppy lands in hill tracts/areas. It checks unnecessary soil loss from gullies and also conserves the rainwater so that vegetation receives adequate amount of water for their growth and development.

(iv) *Tumbling Shifting Cultivation*

It is also known as Sweden agriculture method or slash-and-burn agriculture. It refers to practicing agriculture for few years in forest land/area after clearing vegetation and then left untended while the natural vegetation regenerates. Remoteness, jurisdiction, land tenure and transitory land use are some constraints in refining shifting cultivation. Reducing in area under shifting cultivation by encouraging the tribal peoples for settle agriculture is a very outstanding practice for soil conservation.

(v) *Contour Cultivation or Cultivation Across Slope*

Poor rainfall infiltration resulted due to the high rainfall intensity and high rate of runoff. This method is simple, which decreases the runoff and soil loss on mild sloppy lands successfully. In this method, cultural practices and growing of crops are done on the contours. It restricts the development of rills. The efficacy of this practice varies with intensity of rainfall, soil type and topography. It can be effectively used on medium slopes and on permeable soil. On steep slopes with high rainfall intensity, it may cause formation of gullies (Kampen 1982; Singh 2000; Dadhich and Meena 2014).

(vi) *Intercropping*

Different crops are sown at different times in alternate rows to shelter the topsoil from rain wash. The system involves growing of two or more agricultural crops on the same field, simultaneously. The crop escalation is in both time-based and spatial dimensions. The growing of two or more crops should be complimentary to each other. The maturity period of subsidiary crop should be shorter than the main crop. The crops grown in intercropping should require similar agronomic practices. Erosion permitting and resisting crops should be intercropped with each other. The crops should have different rooting patterns.

Benefits of Intercropping

- High total biomass production.
- Judicious utilization of soil and water resources.
- It reduces the marketing risks due to production of variety of products in different time periods.
- Drought conditions can be mitigated through intercropping.

(vii) *Organic Farming*

An enduring soil cover is a significant measure to guard the land against damage due to the exposure of land to rain and sun. It also alters the microclimate and offers the continuous supply of food to the micro and macro organisms in the soil. It improves soil bio-physico-chemical properties (Ghosh et al. 2010). Kilcher (2007) reported that the organic farmers protect their soil from erosion through different conservation measures such as soil bunds and terraces, minimum tillage and contour cultivation. Growing of cover crops, applying mulching materials, intercropping and agroforestry systems may play significant role in shelter against erosion and landslides.

(viii) *Conservation Tillage*

Growing of crops into no-tilled fields is usually done through quarrying small trenches. No other soil tillage practices were applied in cropping system. Conventional tillage totally reverses the soil, while no-till causes small soil disturbances, and the residues from previous crops remain at the soil surface as protective cover (Gattinger et al. 2011). It increases the soil moisture retention up to 28% as compared to conventional tillage and produces wheat about 1.2 t/ha/year (McGarry et al. 2000). Huge quantity of crop residue left on the surface of soil reduces the evapotranspiration rate and increases water retention capacity in surface soil layer (Blevins and Frye 1993; Rasmussen 1999; Srivastava et al. 2000). The availability of water was significantly higher with zero tillage than conventional tillage system (Bhattacharyya et al. 2006, 2008).

Porosity along with other physical properties of the surface soils is improved by the microorganism (soil biota). It is recognized as "biological tillage" and not tuneful with mechanical tillage. Soil structure will be disturbed through mechanical soil tillage. Minimum tillage practices help to improve infiltration rate, reduce runoff and evaporation losses. It also improves soil health, SOM in the surface soil, soil structure, productivity, soil fertility and nutrient cycling and reduces soil compaction (Gangwar et al. 2004; Hobbs et al. 2008; Kassam and Friedrich 2009; Birch 2011). Gangwar and Singh (2010) reported that the zero-tilled plots experienced minimum infiltration rate (0.75 cm h^{-1}) which was followed by plots where residue burned (1.44 cm h^{-1}) and highest in plots where residues incorporated (1.50 cm h^{-1}). Soil crusting on zero-tilled plots was at a slower rate (Subbulakshmi 2007). The soil fertility and water use efficiency (WUE) were increased due to use of zero tillage or no-till practice (Benites 2008; Ortiz et al. 2008; Yadav et al. 2017).

(ix) *Mulching*

Any kind of material covers soil surface against the action of water and wind. Decrease in evaporation rate, suppression of weeds, protection of the soil against extreme heat and cold incidences, reduce of soil compaction and control of wind and soil erosion are the main advantages of mulching. Organic materials (sawdust, wood chips) have high C:N ratio. So, sometimes it may cause N deficiency. Mulching has potential for adequate weed control along with benefits for water conservation and soil fertility. Mulching is widely used in horticultural plants during dry periods (Fig. 12).

Organic and Inorganic Mulch

Organic mulches are desiccated plant residue that decompose over time after adding to the soil, consecutively improving the water holding capacity of soil and soil fertility and facilitate the activities of earthworms and other microbial activity (Gill and Robert 2010; Chen et al. 2000). Crop straw, dried weeds, yard waste, grass, etc. are the C-based covering materials which can restore valuable soil

Fig. 12 Conservation techniques applied in horticulture plantation

nutrients and should be replaced sometimes. The recommended depth for applying organic mulches needs to be 2–3 inches. It has some disadvantages like thick layer of material may reduce air motion, cause waterlogging during rainy season and attack of root rot diseases and provide shelter for hiding insects. The strawberry (*Fragaria* spp.) yield, water intake, WUE and root growth parameters are significantly affected by the use of irrigation methods and different types of mulches (Singh et al. 1999; Kumar and Dey 2011).

Application of OM for mulching was considered to be an effective management for salt-affected soil amelioration and crop growth (Bhatti et al. 2005; Mulumba and Lal 2008; Pang et al. 2010). Mulches are usually applied to the soil surface to conserve soil moisture, moderate soil temperature and reduce evaporation (Ramakrishna et al. 2006; Pervaiz et al. 2009; Pang et al. 2010; Kumar et al. 2017). A study was conducted to assess the impact of FYM (farm yard manure), polyethylene film mulch, straw mulch, FYM combined with polyethylene film mulch, FYM combined with straw mulch, on soil hydraulic properties and soil mechanical impedance on a typical coastal tidal flat reclaimed saline land. They argued with their conclusion as the soil properties were improved with the application of FYM (Zhang et al. 2014).

Inorganic mulches have longer life span than organic mulches, but not effective as organic mulches for improvement of soil health. Normally, it needs less caution than organic mulch. It can decrease water losses through evaporation and suppress weeds, but cannot improve soil health and fertility. Infiltration may be enhanced by using this technology through the protection of soil surface from soil erosion. However, the practice is costly and labour intensive for transport and application to the soil; it is widely used in India. It is reasonable for cash crops such as vegetables and fruits. The impact of mulching was studied for some fruit crops including litchi (*Litchi chinensis*) (Joshi et al. 2012), strawberry (Gupta and Acharya 1994), apple (*Malus domestica*) (Tang et al. 1984; Lal et al. 2003; Kumar et al. 2014), plum (*Prunus domestica*) (Sharma and Kathiravan 2009), almond (*Prunus dulcis*) (Verma et al. 2001; Sharma et al. 2011a), mango (Sharma et al. 2011b) and citrus (*Citrus* spp.) (Sharma et al. 2011c). Polyethylene covering was a well-known practice that was used for conservation of soil and water resources to increase the crop productivity sustainably.

Surface mulch increases soil moisture and decreases the runoff rate and moving force of raindrops on soil surface (Mutchler and Young 1975; Smets et al. 2008; Bautista et al. 2009; Noura et al. 2015; Prats et al. 2016). Wischmeier (1984) conveyed that the soil erosion was abridged by 93% due to mulch cover. Adekalu et al. (2006) described that the mulching decreases surface runoff during and after rainfall, increases infiltration and moderates soil loss. Simulation for rainfall data also directed that the runoff and soil loss were significantly correlated with the mulch cover. Jordan et al. (2010) conducted an experiment for 3 years with some straw mulching under cultivated soils in semiarid conditions. They found that the application of mulch improved the soil physical and chemical properties and reduced runoff rates and soil loss. In another simulated rainfall study, runoff and soil losses were reduced by increased percent of mulch cover (Osunbitan and Adekalu 1997).

(x) *In Situ Moisture Conservation Techniques*

Bundelkhand region (7.04 M ha) of Central India has undulating terrain, scarce vegetation cover, hostile climate and unfavourable edaphic conditions. Nearly 70% of total area of the region has been affected by varying degree of erosion hazards (Tiwari and Narayan 2010). The soil of Bundelkhand region are adversely affected with the problem of soil erosion, low productivity and even crop failure due to frequent drought and long dry spells during monsoon season. Received rainfall is scanty, erratic and high intensity showers during the monsoon season result in sizable runoff (runoff ranged between 50 and 60% of rainfall and soil loss between 8 and 9 t ha^{-1} at 2% slope on cultivated fallow land in red soils) and soil loss (Lakaria et al. 2010). The survival of horticultural plantation under traditional planting practices is very low on account of low in situ moisture conservation in red soils. Harvesting of rainwater and in situ moisture conservation is the only viable alternative to artificial irrigation. In situ rainwater collecting techniques like full moon, half moon, cup and plate and trench system with various type of mulches (plastic and organic mulch) have been found to be obliging in moisture conservation during critical stages of fruit growth and development under rain-fed condition (Kumar et al. 2012). In the dry regions, water harvesting is an outstanding method for increasing productivity (Ghosh 1982; Oweis and Hachum 2003, 2006).

(xi) *Zabo System*

The Zabo term means the "seizing runoff water" in the local language. It is a system of water harvesting of Kikruma, a quaint village settled in a rain-shadowed area of Phek district of Nagaland. It combines forest, agriculture, horticulture, fishery and animal husbandry with well-originated SWC measures (Fig. 13). Development of water resources and protection of environment are vital aspects of the system (Sharma et al. 1994). It can be practised by single farmer as well as group of 10–15 farmers. Peoples of the village suffer from water scarcity due to surface runoff. This condition forced people to conserve rainwater and use it judiciously. It has an intrinsic water harvesting and recycling capacity with enough management measures (Pulamte 2008). The system involves the following steps:

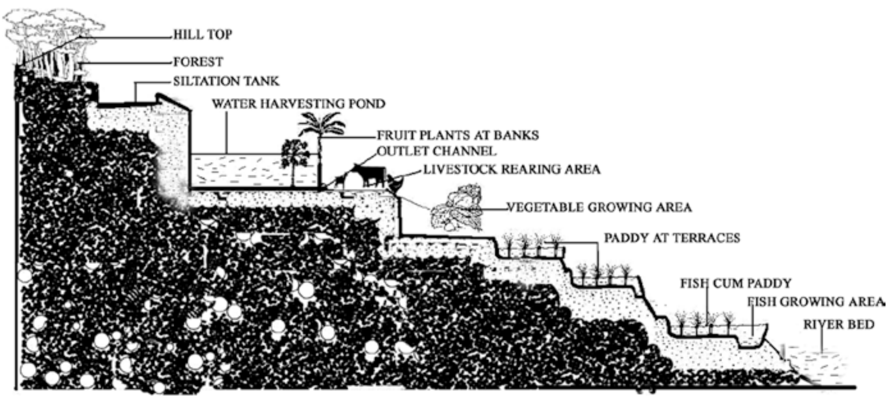

Fig. 13 Land management in ZABO farming. (Source: Singh et al. 2018)

Construction of Water Harvesting Ponds: Ponds were constructed in the middle to collect water, and the bottom surface of the pond is well treated to curtail the loss of water through seepage. On hill tops, the protected forest lands act as catchments, and water is channelized through inlet channels. Silt holding tanks/chambers were constructed at some points before the runoff water reaches to the pond. Bamboo pipes were used for irrigation purpose (Singh 2007a, b, 2018).

Sharing of water and Repairing of Ponds and Channels: The water sharing among different family takes place through mutual talks. Water is required during growing period of paddy crop. Repairing of ponds was carried out in March or April, during which ponds dry up. All the beneficiary families were involved in pond repairing work.

Selection and Placement of Different Farming Activities: Cultivation of vegetables and fruits was carried out on the banks of the pond. The cattle reared area was fenced with bamboo and wooden branches. Construction for rearing of livestock was prepared at lower side of the water-harvesting pond. In this system, rice fields were located at the lower elevations.

Under this system, the yield of rice ranged between 3 and 4 tonnes per hectare (Sharma and Sharma 2003). Rice+ fish cultivation is commonly practised. In July month, a small pit was made in the centre of the paddy field, and fish fingerlings were released in the fields. After the maturity of rice, the field dries up. As the field dries, fishes move into the pit, and from there, fishes are harvested. Around 50–60 kg of fish was harvested per hectare from rice + fish cultivation.

(xii) *Integrated Hill Development Model*

The module is based on watershed management practices (Fig. 14). This module is widely accepted in the hilly areas for effective rainwater harvesting and increasing opportunity of irrigation. It was developed by ICAR Complex under a

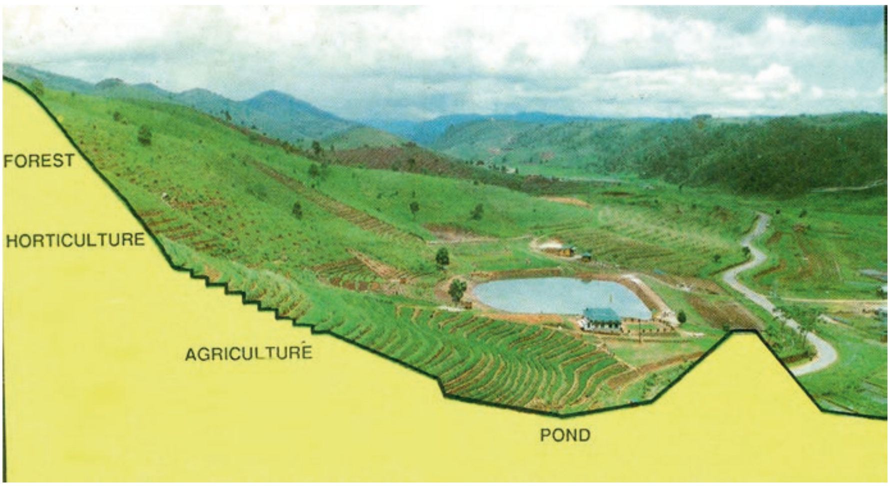

Fig. 14 Combined hill development model

multidisciplinary research programme and was pointed at evolving substitute land management practices. The mixed land use systems such as agri-horticulture and silvi-pasture incorporate a secondary source of family income through livestock rearing and pisciculture. The construction of water collecting and silt holding structures were built at lower elevated areas.

8.2 Mechanical/Engineering/Structural

8.2.1 Terracing

(i) *Bench Terracing*

It is a step-like field along the contour lines generally by half cutting and half filling technique (Fig. 15). The sharp angle is finished and changed into the number of level fields. Thus the threats of soil loss are decreased due to cutting down the continuous flow of runoff. The slope degree and length were reduced. It may be suggested for the lands having slope up to 33%, but due to some socio-economic conditions, it may be adopted for land having slope up to 50–60%.

Bench Terraces with Stonewalls: Where plenty of good-quality stones are available, bench terracing with stone walls was recommended for SWC to enhance crop productivity. It is mostly applicable for cash crops and perennial tree plantations.

Half-moon terraces: Semi-circular-fashioned terraces were prepared at the downstream side of the plant.

(ii) *Gradonies*

These are narrow bench terraces having steep inward slope and made on contour lines (Fig. 16). Uniform steep sloping lands were suitable for afforestation with such kind of conservation measures. Generally, vertical interval and width should be kept from 1.0 to 1.5 m; it may depend on slope steepness. Soil excavated from the inner side of the gradonies is heaped on the outer edge with an inward slope of 7.5:1. Pits of 50 cm × 50 cm × 50 cm at middle of the gradonies were dug at 3 m spacing for planting of tree species (Mahnot and Singh 1993).

Fig. 15 Terracing in hilly areas of India

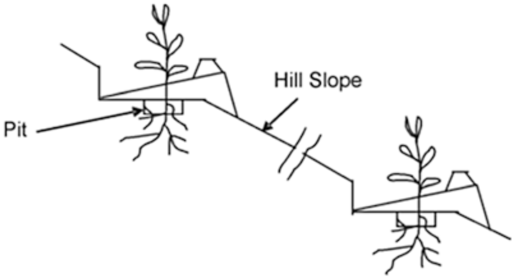

Fig. 16 Cross section of a Gradoni. (Source: Mahnot and Singh 1993)

8.2.2 Bunding

(i) *Contour Bunding*

To check the runoff flowing down the slope, contour bunds were laid out in field to conserve moisture and to reduce erosion losses. In areas having 2–6% slopes with low or irregular annual precipitation (< 800 mm) and permeable soils, this measure is recommended for conservation of soil and water resources. The erosive velocity is the main criterion for spacing of bunds. It may depend on length of slope, slope steepness, rainfall, cropping intensity and conservation practices. The vertical intervals between two bunds are known as spacing of bunds.

(ii) *Graded Bunding*

Graded bunds are laid along a prearranged longitudinal grade instead of a contour up to 10% land slope for safe draining of excess runoff. It is best suited in areas receiving rainfall > 750 mm and soils having infiltration rate <8 mm/h.

(iii) *Peripheral Bunds*

Bunds made around the gully head to prevent the entry of runoff into the gully. It shields gully head from the losses caused through erosion. It facilitates environment for vegetative measures on gully heads, slopes and beds.

8.2.3 Trenching

It is widely used for moisture conservation in the established new plantations. The trenches were dug up at contour lines for rainwater harvesting in cropped area where the slope is <30%. On the downstream side of trench, bunds were formed. After 3–4 years, the vegetation helps in conservation. It cuts down the speed of runoff and conserves the overflow. The captured runoff infiltrates through the soil gradually and is made available to the plants.

(i) *Continuous Contour Trenches*

There is no discontinuity in trench length (10–20 m) which may be reliant upon the size of the field, known as continuous contour trenches. Continuous contour trenches were normally used in low-rainfall areas (Fig. 17).

Fig. 17 Continuous contour trenches. (Source: CGWB 2018)

(ii) *Staggered Contour Trenches (SCTs)*

Generally, SCTs were prepared in high precipitation areas, where the risk of overflow is prominent (Figs. 18 and 19). Such trenches are placed in alternate rows directly beneath one another in a staggered manner. SCTs are 2–3 m long with 3–5 m spacing between the rows. Based on the slope of land, tree species were planted in SCTs. This measure is very effective in averting extension of gully head, soil loss and capture of overflow.

(iii) *Semi-elliptical Trenches*

The trenches of 2 m length, 0.45 m top width, 0.30 m bottom width and 0.45 m depth were constructed in a semi-elliptical style on the upstream side of the plant. Two rows of *Stylosanthes scabra* (shrubby stylo) followed by one row of vetiver at a spacing of 50 cm were planted as vegetative barriers on the downstream side of the trench bund.

8.2.4 Loose Boulder/Loose Stone/Dry Stone Masonry Check Dams

In steep and broad gullies, these structures are effective for checking runoff rate (Fig. 20). These were the most appropriate structures at higher elevation areas of the catchment. They have longer life and require less maintenance. The bed of the gully was excavated for keeping uniform depth of about 0.3 m. Flat stones of size 20–30 cm are the best for construction and laid in such a way that all the stones are keyed together. Large-sized stones are placed at the centre of the dam, and gaps between stones may be filled with small pieces of stones. In the middle of the dam, enough spillway is provided to allow to discharge the rainfall runoff (Goyal et al. 2007).

Fig. 18 Staggered contour trenches

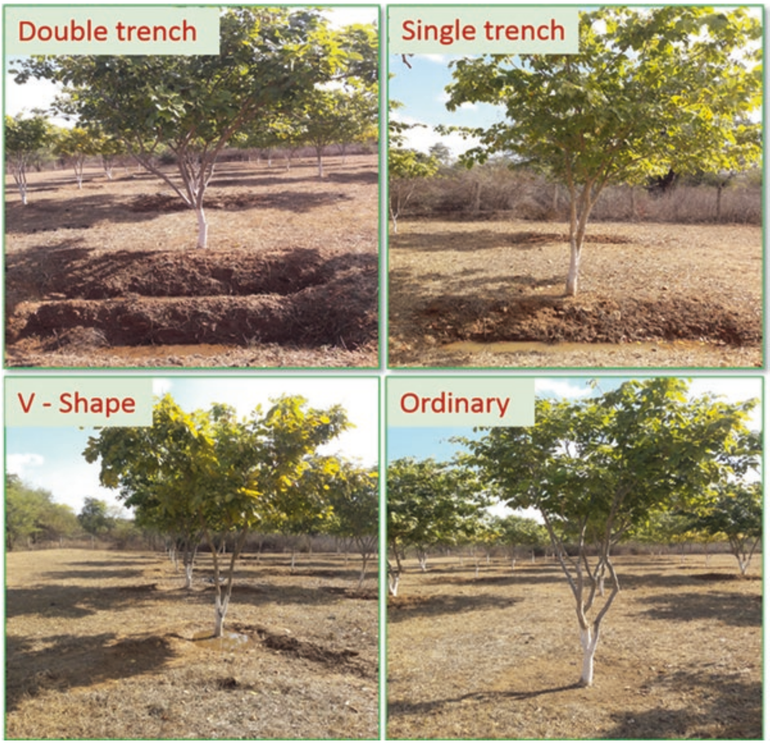

Fig. 19 Conservation measures applied in tree plantations

Fig. 20 Loose boulder checks. (Source: https://www.hydratelife.org/the-story-of-ralegan-siddhi-bringing-water-back-to-life/)

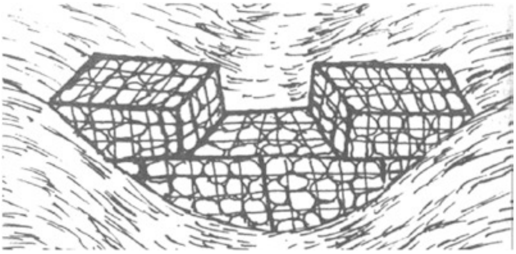

Fig. 21 Wire Gabion

8.2.5 Gabion

Semi-permanent structures of stone wire crate (Gabion) were generally used for the treatment of farm drainage lines (Fig. 21). The check dams prepared by using gabions are also used for treating the second- and third-order (main) gullies. Loose boulders are walled with wire mesh to reinforce the structure. It is a semi-permanent mechanical construction suitable in sharp slanted gullied areas to check sedimentation in water bodies.

8.2.6 Stop Dam

A structure is made of loose rocks, boulders, brush, wires, etc. as concrete or masonry barriers constructed on small streams (Fig. 22). It is a barrier constructed across the way of water flow in shallow rivers and streams. It is built for the purpose of water harvesting for irrigation as well as for domestic and animal use.

8.2.7 Check Dam

(i) *Brushwood Check Dams*

Branches with spines of the tree and or shrub species were staked in two rows parallel to each other and across the gully or nala. Branches were filled with brushwood between the two parallel rows (Fig. 23), whereas at the top, staked branches were fastened with small sticks. These are generally prepared in small and medium

Fig. 22 Bagra Walla stop dam. (Source: State Planning Commission 2008)

Fig. 23 Check dams. (Source: https://www.escondido.org/Data/Sites/1/media/pdfs/Utilities/BMPCheckDams.pdf

gullies for regulating overflow and the places where long lasting protection is followed by growing vegetation. It holds definite volume of soil to establish flora. Planting material of tree species was established in 0.3 m × 0.2 m trenches crossways the gully. The brushwood was wired around the posts/tree planting material/cuttings. Brushwood check dams reduce the velocity of runoff and help in reduction of soil loss. Soil material deposited behind the structures increases the availability of moisture. Such condition improves the success of growing vegetation barriers in gullied area.

(ii) *Live Vegetative Check Dams*

The catchments having low erosion problems can be effectively managed through establishing such live vegetative checks. Perennial shrubs, small tree and grass species which were easily available used for treating gentle sloppy catchment areas. The cost of establishing such permanent structures of vegetation is low. These structures also provide fodder, fuelwood, fibre, food, etc. for the local people. The vegetative barriers were grown in staggered two rows across the water current in small gullied area. The shrubs like century plant, *Arundo donax* (giant cane), *Capparis aphylla* (karira), bush morning glory, lantana, *Grewia spp.*, *Clerodendrum phlomidis* (arni), etc. can be used for live vegetative check dams. Seeds of perennial grass species should be broadcasted behind dams; it binds soil particles together and gives additional strength for shrubs.

8.2.8 Crib Wall

It comprises a hollow, box-like meshing sequence of unprocessed logs (Fig. 24). Structure is loaded with appropriate backfill material and layers of live branches. Crib wall should be successfully built on an evenly sloped surface. The

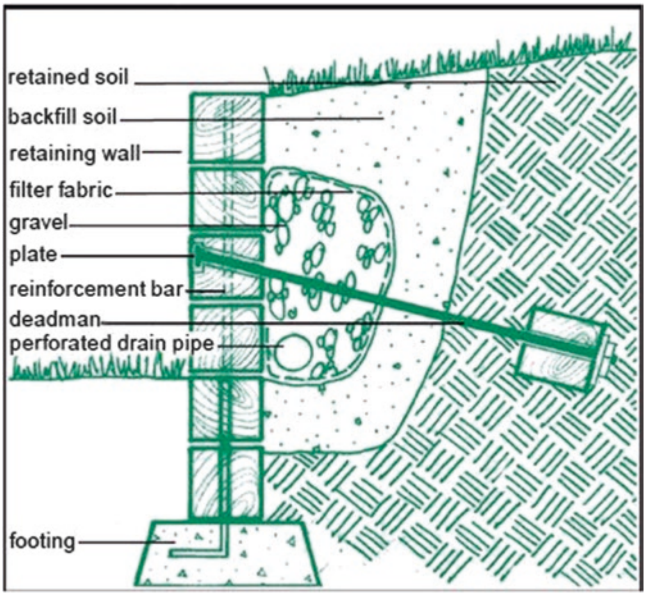

Fig. 24 Crib wall. (Source: https://web.mst.edu/~rogersda/umrcourses/ ge441/online_lectures/retention_structures/GE441-Lecture6-2.pdf

Fig. 25 Diversion drains. (Source: http://awm-solutions.iwmi.org/river-diversions.aspx)

places having limited space and a more vertical structure is obligatory, it is an appropriate technique. It delivers instant safety from soil loss, whereas established vegetation offers long-term stability. Appealingly, it is more pleasant and perhaps less lavish.

8.2.9 Construction of Proper Drainage

(i) *Diversion Drains*

The channels are constructed to divert runoff water away to safeguard the downstream area and release it carefully (Fig. 25). It can be applied in an initial stage of controlling runoff losses in high rainfall areas. Generally, the siltation problem with narrow and deep ditch is very less as compared to broad and shallow ditch. Soil dug from the ditch should be dumped on lower side of the drain. Outlet end should be opened at natural drainage lines. Grasses such as *Panicum repens* (torpedo grass), para grass, *Cynodon plectostachyus* (stargrass), *Cynodon dactylon* (doob grass) and *Paspalum notatum* (bahiagrass) have been found suitable to grow at the outlet end of diversion drain. Timely removal of weeds, filling of the areas with grass and proper cutting of grass are the maintenance operations that should be taken into consideration for proper functioning of diversion drains in rainy season.

8.2.10 Khadin

Work on participatory watershed management was carried out at CAZRI and demonstrated improved land management practices in village Baorli-Bambore. Khadin structure (Fig. 26) improves water availability and generates revenue of Rs.18,500 ha^{-1} from fodder production during the extreme drought year of 2002 (Mishra et al. 2011).

Fig. 26 A Khadin in the Baorli-Bambore watershed near Jodhpur. (Mishra et al. 2011)

8.3 Efficient Water Management

Conservation and judicious utilization of water is a most important strategy for sustainable agriculture production. These are some strategies given below which help to overcome the scarcity of water in the country.

- System of Rice Intensification (SRI method) has the capacity to save 40–50% water and to increase 3/4 t/ha yield.
- Use sprinkler and drip irrigation.
- Use mulching in arid and semiarid areas.
- Sewage water should be treated and used for irrigation purpose.
- Training should be given to the farmers for water management.
- Demonstrations were organized in villages and in the farmer's field to use water carefully.

Slow application of water on, above and below the soil through surface drip, subsurface drip, bubbler and micro sprinkler systems as continuous drops, tiny watercourses or small sprays is known as micro-irrigation system. Central and state governments often promoted micro-irrigation methods, because of the growing water crisis where Indian agriculture sector consumes 80% of the freshwater. Micro-irrigation is a policy matter, due to frequent drought periods in 2012, 2015 and 2016 in India. According to central government's new slogan, "Per Drop More Crop" government prepared one yojana/programme (Pradhan Mantri Krishi Sinchai Yojana) and try to move towards micro-irrigation to "save" water and increase crop productivity (Harsha 2017).

9 Programmes/Projects/Schemes/Yojana for SWC (Source: Sivanna 2009, Bhan 2013; Ministry of Agriculture 2014; MRD 2017; Central Water Commission National Water Academy 2017)

- *National Watershed Development Project for Rain fed Areas:* Project was launched in 1990–1991 based on Integrated Watershed Management and Sustainable Farming Systems. Presently, the project is implemented based on guidelines given by National Rainfed Area Authority for Watershed Development Projects.
- *Soil Conservation in the Catchments of River Valley Project and Flood-Prone River:* It was implemented during 1961–1962 in 31 catchments of 18 states and flood-prone (FPR) areas in 10 catchments of 9 states. It starts with aiming at preventing the siltation of reservoirs and improving productivity of catchment areas through integrated watershed management with suitable measures such as vegetative hedges, contour/graded bunding, agroforestry, horticulture plantation, developments of silvi-pasture and pasture, afforestation, drainage line treatments, water harvesting structures, percolation tanks, sediments detention dams, etc. in agricultural, forest and wastelands.
- *Reclamation and Development of Alkali and Acid Soils:* It was launched during the 7th Five-Year Plan. It is enduring in Haryana, Punjab and Uttar Pradesh. It includes provision for improving physical conditions and productivity of alkaline soils. Supply of assured irrigation water for levelling of land, bunding and deep ploughing, drainage systems at community places, use of soil amendment for treating alkali and acidic soils and application of organic manure are the main components of this scheme. About 0.89 million ha area was covered up to 2011–2012 under this scheme.
- *Watershed Development Project in Shifting Cultivation Areas:* The shifting cultivation is prominent in north-eastern region of India. This scheme was launched during 1987–1988 and covered seven states of the north-eastern region and area of Andhra Pradesh and Orissa states. This scheme focused on Jhumia families with providing appropriate soil conservation measures and watershed management.
- *Drought-Prone Area Programme and Desert Development Programme:* The drought-prone area programme, desert development programme and food for work programme were initiated in 1972–1973. The watershed management approach was adopted in these programmes during 1987. The 15.2 million ha area was covered under drought-prone area programme and 9.0 million ha under desert development programme during 2011–2012.
- *National Afforestation Programme:* Four centrally sponsored afforestation schemes, i.e. area-oriented fuel wood and fodder project scheme, Integrated Afforestation and Eco-development Project Scheme, Conservation of Non-Timber Forest Produce including medicinal plants and Association of ST and Rural Poor in Regeneration of Degraded Forests, were run by the Ministry of Environment, Forest and Climate Change during the 9th Five-Year Plan. According to recommendations from the above four schemes, a Pilot Scheme, 'Samnavit Gram Vanikaran Samridhi Yojana' was launched in 2000–2001 and delivered through Forest Development Agency and Joint Forest Management Committee.

- *National Project for Repair, Restoration and Renovation of Water Bodies:* It was launched in 2005 for repair, restoration and renovation of 1098 water bodies in 26 districts of 15 states to improve an irrigation potential. After the success of this scheme, the ministry applied this scheme as a state sector scheme.
- *River Valley Project and Flood-Prone River Programme:* The scheme was started in 1961–1962 and executed in 2000 through Macro Management of Agriculture in 60 selected catchments of all states of India (excluding Goa). The scheme/project was aimed at conservation of soil and water resources through integrated watershed development programmes. Different conservation measures such as vegetative hedges at contour lines, contour/graded bunding, horticulture plantation, staggered contour trenching, plantation of MPTs, silvi-pasture development, pasture development, digging of farm ponds, percolation tanks and drainage line treatment (earthen loose boulders, drop spillway, sediment detention structure, etc.) were used in watershed management.
- *National Rural Employment Guarantee Scheme:* It was launched in 2005. In the first phase, it was notified in 200 districts during 2006 and then extended in 130 districts during 2007–2008. The rest of districts were notified in 2008, so the act covers the entire country. Under this act, the government is providing employment on different activities for SWC.
- *Integrated Wasteland Development Projects:* It was directed by the National Wasteland Development Board in 1989, aiming at wasteland development based on watershed management.
- *Hariyali:* The Government of India during 1994 gives specific guidelines for implementing watershed development activities. These guidelines were revised in 2001, and local communities brought at centre stage. The Ministry of Rural Development in 2001, for uniformity in coverage of all the watershed activities were brought under the Department of Land Resources, which were reviewed in 2003, and the scheme is known as "Hariyali".
- *Pradhan Mantri Krishi Sinchai Yojana:* The yojana was launched in 2017 with setting a vision of secure irrigation access. New appoaches such as "Har Khet Ko Pani" improve on farm WUE, "More Crop Per Drop" with an "Integrated Value Chain" were involved in this scheme.
- *Mission of Water Conservation:* The Ministry of Water Resources, Government of India, prepared the guidelines for "Mission Water Conservation" and shared with all the states in 2016–2017. The Ministry also identified 2264 water-stressed blocks from 324 districts of 21 states of India for execution of the mission.
- *National Mission for Sustainable Agriculture:* The Department of Agriculture and Cooperation Ministry of Agriculture, Government of India, issued the operational guidelines in 2014. It was formulated for refining crop productivity especially in water-scarce areas. The scheme was mainly focused on increasing WUE, integrated farming, soil health management and conservation of natural resources. The special emphasis was given on conservation of soil and water resources through increasing WUE, soil health management and development of rain-fed areas.

10 Women and SWC

Among most of the farmer communities, women are actively engaged in farming systems. The conservation of natural resources for sustainable agriculture is the prime need, and women are well aware about that due to their involvement in such activities. Their awareness about improving soil health includes addition of litter or crop residue is most appreciable. Due to such activities, environmental pollution gets reduced through restricting the burning of crop residue. The women from the villages who depended on the forest for their daily needs restrict woodcutters from deforestation. This movement is known as CHIPKO. In the next step, they are involved in afforestation programmes which provide safe drinking water for villages. Johnson et al. (2013) who assessed the role of rural women in watershed development project in Reddiyarchatram block of Dindigul district experienced active participation of rural women in the project and help in improving their economic condition. Seeley et al. (2000) stated that the women played a vital role in agriculture along with natural resource management activities. They also revealed that their efforts generate more income and cut down the risk of failure.

11 Efficacy of Sustainable Techniques Towards SWC

An efficiency of SWC is a vital technique for the peoples adopting the technologies and for technology promoter. Technology should benefit more with a minimum cost. Efficiency of different techniques used for SWC can be measured by three ways, i.e. conservation of degraded lands, economic returns and adoption of SWC technologies (Reddy et al. 2004) (Table 7).

Table 7 Economic incentives and adoption level of selected SWC practices in India (Reddy et al. 2004)

SWC technology	Adoption/ sustenance rate	Level of incentives	Reason
Contour strips in maize coupled with green manuring	High	High	Direct increase in yield
Graded bunds to dispose excess water	–	Medium	Performed well
Terracing	Medium	High	Checks soil erosion and higher yield
Compartmental bunding	Low	Low	No additional Pearl millet yield
Opening of dead furrow	High	High	Easy to adopt with less investment
Contour cultivation	Low	Low	Difficulty in farm operations
Vegetative barriers	Medium	Low	Insignificant/marginal yield
Water harvesting structures	High	High	Direct access to irrigation water

When the land degradation rate exceeds the conservation rate, it may indicate that the lack of adoption of SWC techniques farmers and results in low efficacy of SWC techniques. Farmers point of view, SWC techniques as an only investment and their economics which may play conclusive role in the adoption of technologies (Kerr and Sanghi 2002; Pande et al. 2011; Datta et al. 2017). Low returns from the SWC measures in early stage could be a hindrance in adoption of SWC measures. Therefore, such SWC measures are more efficient in long terms. Atampugre (2014) reported that the bench terrace was economically more efficient than contour bunding and strips of Napier grass (*Pennisetum purpureum*).

Contour bunds and contour farming were recommended on large scale in the 1930s, whereas some operational problems and dearth of superficial economic gains from such practices were not adopted. Analysing some success stories of SWC measures, it has been recommended that there should be a provision of irrigation components such as water harvesting structures, farm ponds, earthen bunds, etc. Such practices may strengthen farmers economically which increases the efficacy of SWC techniques. Benefit to cost ratio, net present value and internal rate of return were higher for SWC practices with irrigation component than without irrigation component (Chandrashekar 2003).

Many researcher enlisted benefits provided by SWC techniques used in conservation agriculture such as high C sequestration resulting in high SOM. It helps in increasing soil fertility, decreases weed infestation, increases water and nutrient use efficiency, enhances productivity up to 4–10%, reduces soil nutrient loss and environmental pollution due to restricting residue burning and use residue as mulch and better crop diversification (Saharawat et al. 2012; Jat et al. 2005, 2012; Gathala et al. 2011; Sidhu et al. 2007; Malik et al. 2005).

The level of conservation activity influenced by the objectives of scientist and farmers affects the efficiency of conservation measures (Kerr and Sanghi 2002). Discouraging factors such as vegetative barriers are prone to pest attack may affect the adoption of SWC measures by some farmers. So, the motivation is required for such farmers and also needs to told them about benefits getting from SWC measures.

Sultan et al. (2018) highlighted the impact of agro-ecological environment in efficacy of conservation measures and high spatial variation within and between land use systems. It may cause deviation in SWC efficiency. They reported about 32 to 51% runoff conservation efficiency of three techniques of SWC applied in cultivated land.

12 Ecological Sustainability: An Agricultural Perspective

Natural resources exploited by the present generation in such a manner that the capability of resources should provide services for coming generations is known as sustainability (Ekosse 2009). Capacity of ecosystems to sustain their essential function, processes and retain their biodiversity is known as ecological sustainability (Mukoni 2015). When it is applied in agriculture with covering the ecological aspects, then it is known as ecological sustainability of agriculture. Ecological sustainable system is a combined system of production practices having a site-specific applicability which meets the human needs of food, water and fibre and augment environmental quality over long time period.

Nowadays, achieving ecological sustainability is a major challenge due to continuous increase in human population of the country. In the country like India, increasing productivity of agricultural lands is the one most important option for feeding the huge amount of population (Shukla and Dwivedi 2015). The productivity can be increased by judicious utilization of available natural resources and through increasing output by appropriate use of farm inputs. Sustainability of agriculture may be ensured through the following points (Swaminathan 1995; Thompson 1996):

- Amalgamation of natural processes such as cycling of nutrients, atmospheric N fixation and control of insect-pests through biological measures.
- Cut down the use of nonrenewable inputs that harm human beings and the environment.
- Involvement of farmers and rural people in problem analysis, development and adaptation of technologies, their extension, monitoring and evaluation processes.
- Unbiased and judicious use of natural resources.
- Use of local knowledge about practices and resource conservation, appropriately.
- Use of farming systems which goes for natural resource conservation and their prudent utilization.

Indicators such as quality of natural resources, agroecosystem biodiversity and agricultural productivity were used to determine ecological sustainability. Collection of data on the above-mentioned indicator is a very tough job due to gaps in data and the quality of the data. Pandey and Singh (2012) enlisted the number of indicators such as improved soil fertility, high OM in surface soil, high nutrient concentration and water moisture in surface soil, increase in crops, microbes, plant and animal diversity, reduction in soil erosion, landslides and enhanced green cover, improved C sequestration and reduced energy demand for ecological sustainability of agriculture systems. Conservation agriculture is one step towards the ecological sustainable production systems, and its necessity is to translate it into site-specific practices (ICRISAT 2006; IARI 2012).

13 Future Prospects of Sustainable Practices Promoting SWC

Demand of food, fodder, fibre and firewood is increasing in higher rate as continuous increase in the human and livestock population. So, the people may adopt conventional farming system along with conservation farming systems. The demands of human being can be fulfilled through applying sustainable agriculture practices.

As review of currently used SWC measures/techniques, SWC techniques are the main concern for sustainable agriculture. The following points are more important for future concern of the SWC measures and their adoption for sustainable agriculture production:

- Need refined efficient SWC techniques for sustainable agriculture in all agroclimatic zones of India.
- There should more emphasis on participatory approach for the successful programmes developed by government departments and non-governmental organizations.
- There should continuous efforts of government and other external agencies in SWC.
- Work-related artificial recharge to groundwater is the main concern for sustainable farming systems.
- Evaluation of all watershed projects/programmes for understanding possible positive and negative impacts to make necessary corrections.
- Monitoring and assessment programmes to study efficacy of SWC measures.
- Public awareness on SWC.
- Decrease unnecessary use of water for domestic and other purposes.
- Recycling of waste water through modern techniques.
- Formulate policy, acts and rules and promptly follow them for judicious utilization of soil and water resources.

14 Conclusions

Salinization, flooding, drought, erosion and waterlogging, deforestation, overgrazing and conventional agriculture are some measures of soil degradation. Among these, soil loss by water is the most solemn problem in India, as it far exceeds the natural soil formation rates. It accounts 93.7 M ha area under soil erosion due to runoff, whereas 9.5 M ha area degraded due to wind erosion. About 5334 M tonnes of soil are eroded annually in the country due to water-forced soil erosion. The 29% of total lost fertile soil is permanently lost into the sea, whereas 10% deposited in the water bodies, and the 61% is facing major degradation problems (Bhattacharyya et al. 2015; Meena and Meena 2017). Crop productivity declines due to unavailability of proper soil and water resources. In the last 2–3 decades, without any groundwater recharging system, use of tube wells for pumping groundwater to irrigate agriculture farm is increasing continuously. It results in fluctuation in groundwater level; it serves as a main constrain in crop productivity. Use of vegetative such as planting of MPTs, agroforestry measures, agricultural measures and engineering measures such as terracing, trenching, bunding, stop and check dams, crib wall, khadin and diversion drains showed positive impact on natural resource conservation and productivity of crops. The vegetative measures improve soil bio-physicochemical properties and also conserve soil and water resources through reducing erosion losses. Use of vegetation and mechanical measures in combination will help a lot for achieving the goal of sustainable development. Conservation of degraded lands, economic returns from such conservation measures and their adoption by farmers are the deciding factors of efficiency of SWC techniques. Formulation of policies, acts and rules for some important problems is identified and their strict application is the future of such SWC measures.

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Soil for Sustainable Environment and Ecosystems Management

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Abstract

India shares 2% of the world's geographical area supporting 18% human population and 15% livestock population. Soil is the largest pool on the earth having the capacity to sequester and store a million ton of C (carbon) as soil organic carbon (SOC) pool and in plant as vegetation's C pool. It helps to reduce atmospheric C and minimize free movement of several GHGs (greenhouse gases) in the atmosphere which forms the basis of global warming which is a major concern today. Soils support all organisms (perennial trees as vegetations, crops, animals, and humans) and harbor a variety of organisms (both micro and macro) which is prerequisite for smooth functioning of the ecosystem. These entire organisms link among them and help in augmenting quality and health of soils through decaying and decomposition of dead plants (by microorganism, earthworm, etc.) and release several essential nutrients which is the basis of life for plant, animal, and humans. Although, healthy soil gives better ecosystem services along with environmental, ecological, and food and nutrition security (FNS). From an Indian perspective, major soil type includes Inceptisols (95.8 Mha), Entisols (80.1 Mha), and Alfisols (79.7 Mha) sharing 77.76% of land cover. C sequestration capacity of soil is a very good strategy for targeting the goal of FNS along with enhancement of soil health and quality. Good soil can enhance productivity of both land and crops, which secure food and nutritional consumption of varying organisms and sort out the problem of food insecurity. The present chapter deals with the issues related to soil, environment, and their sustainability perspective. In this context, sustainable soil management (SSM) performs good job and helps in maintaining organic carbon (OC) stock which improve fertility and physiochemical properties of soil that significantly affects yield parameter of crops (productivity), water availability and use efficiency, and health of soil-inhabiting organism and whole ecosystem processes.

Keywords

C sequestration · Ecosystem services · Biodiversity · FNS · Soil health

Abbreviation

C	Carbon
CO_2	Carbon dioxide
FNS	Food and nutrient security
GHGs	Greenhouse gases
MEA	Millennium ecosystem assessment

N	Nitrogen
OC	Organic carbon
OM	Organic matter
SOC	Soil organic carbon
SOM	Soil organic matter

1 Introduction

Soil is the largest life-sustaining natural resource, which supports the life of all living organism, and there is an intricate relationship among soil, plants, animals, and human systems. All these components are dependent upon each other for their life sustenance which makes better environment and healthy ecosystem. In turn, healthy and smooth ecosystem and environments make better room of survival for these components, viz., plants, animals, and humans. Thus, soil health is the central concept and a basis for crop health, farm health, forest health, food and nutrition quality, and animal's (both livestock and wild) and human's health. Efficient water and nutrient cycling, maximization in water holding capacity, optimum rate of infiltration, controlled erosion and runoff, checking sediment and nutrient erosion, optimum application of inorganic fertilizers, soil microorganism health, mitigation of drought and floods, high productivity and quality food, and resilient climate through carbon (C) sequestration are the several benefits which is obtained from the healthy soil. But soil structure damage, loss of essential nutrients, less organic matter (OM)/C, and soil erosion and runoff phenomenon can affect the health status of soils and food security (Lal 2009; Brevik 2013; Pimentel and Burgess 2013; Meena et al. 2018).

Decay and decomposition of several dead flora and fauna represent the stock of OM and C in the soils. The quantity of soil organic carbon (SOC) is variable in terms of spatially and temporally throughout the globe and influenced by several biotic and abiotic factors (Weissert et al. 2016). Globally, around 1500 PgC of SOC stock has been reported in 1 m of top soil (FAO and ITPS 2015), and the region of wetlands and peat lands represents high quantity of C stocks in soils and mostly in the tropics and permafrost region (Gougoulias et al. 2014; Kochy et al. 2015).

The SOC pools vary as per soil types, orders, suborders, and management practices of soils. The soil order Gelisols contributes maximum SOC pools as 316 billion tons followed by *Inceptisols* (190 billion tons), and least (20 billion tons) has been contributed by Andisols order of soil (Eswaran et al. 2000). Similarly, as per one estimate, around 30% (4.03 billion hectare land) area of the earth is covered by forest, of which tropical (in the region of Southeast Asia) and boreal forest (having peatlands) comprises huge amount of soil C (Pan et al. 2013). But deforestation contributes the loss of huge amount of C as 25% of the total stocks of soil C (FAO and ITPS 2015). It is a well-known fact about sequestration and storage capacity of C in both plants and soil which helps in mitigating changing climate and global warming (Jhariya 2017a; Raj et al. 2018). Therefore, SOC play subtle contributions in soil fertility enhancement along with assuring benefits of food and nutrition security (FNS). Thus, SOC assure soil quality which can enhance productivity, soil physicochemical properties, and water and nutrient use efficiency that results in improvement in plant growth conditions (Zdruli et al. 2017; Sihag et al. 2015).

As we know, the rate of changing climate is undeniable and has a sturdy impact on the whole ecosystems including agriculture in terms of food unavailability and shortage, i.e., food insecurity (IPCC 2007; FAO 2015). Also, plenty of soil organic matter (SOM) (or SOC) is very much essential for land development in the farmland and forests area. In this context, practices of sustainable soil management (SSM) can boost this significant effect of SOC through better soil health and quality.

In view of the above, this paper represents the study comprising significant effects of soil and soil containing OM/OC on agriculture, forestry, agroforestry, livestock, humans, and several ecosystems. The role of soils and soil-inhabiting organism in storage and sequestration of C along with substantial contribution of scientific farming practices such as agroforestry in absorption of C (as total C stocks) is also explored. This chapter also throws a light on nexus among soil health, productivity, FNS, and environment security (by the process of C sequestration). Soil conservation and management; good ecosystem services; soil health and productivity; enhancing yield capacity; food, environment, and livelihood security; etc. are the other paradigms of SSM in the changing climate and global warming.

2 Soil: A Friend and Foe

Of course, soil is our friend and a treasure beneath our feet. Soil means the soul of infinite life and makes a connection with our soul and society. We directly and indirectly depend upon soil for our existence. Many peoples in our society, educational institution, and government places consider soil as dirt, which means it makes thing dirty, but it is a wrong observation. This dirt holds billions of onuses upon it and provides various ecological services that sustain our life. Likewise, soil containing OM performs better functions in fertility and productivity improvement and overall land development. Soil-inhabiting organisms like earthworm (also known as farmer's friend), protozoa, and several microorganisms like bacteria, fungi, etc. work for the benefits of plant and other animals including humans. This relationship is basically mutualism as if we adopt better SSM practices, and then these all soil-inhabiting organisms will perform superior works for healthy environment and ecosystems (Lal 2009).

3 Soil: The Essence of Life

Along with air and water, soils hold equal importance and one of the biggest natural resource that sustains life and ecosystem processes. Soil is the fundamental part of our life. Soil gives supports to the root of plants and provides an essential nutrient which is the foods for plants and basis of life (Fig. 1). Thus, without soil we can't

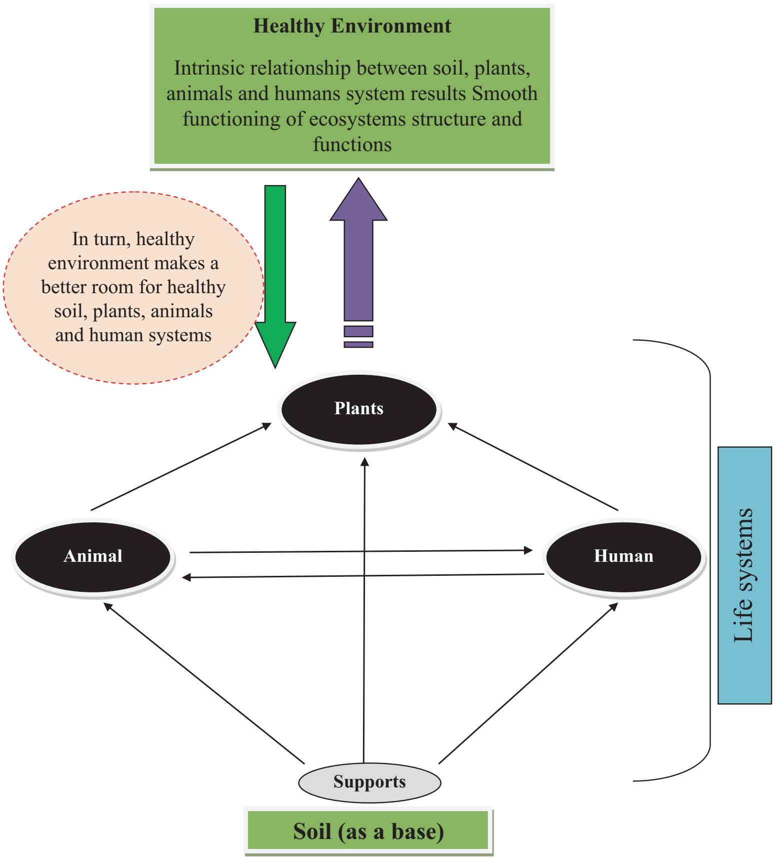

Fig. 1 Nexus between soil, plant, human, and animals for healthy environments. (Singh et al. 2017)

imagine to live. Soil stores various trace metals which are essential for the existence of plants and soil-inhabiting organism, but its low presence (below optimum requirement) represents nutrient deficiency, and above tolerance limit results in toxic effects on biodiversity (Hopkin 1989; Van Straalen and Roelofs 2007; Ram and Meena 2014; Jhariya and Raj 2014; Jhariya et al. 2018a). Similarly soil provides both direct and indirect benefits. Their importance relies upon its ecosystem services. Regulation of water and its availability, availability of plant required essential nutrients, home of several soil-inhabiting organisms (bacteria, fungi, protozoa, earthworms, etc.), habitat for vegetations and wild animals, etc. are the major essential characteristic of soil that shows its essentiality for earth's life and ecosystem processes.

4 Soil Organic Carbon

Decaying of flora and fauna helps in the accumulation of C (both organic and inorganic forms) in the soil that reflects the fertility status of the soil. Moreover, decomposition releases the various essential nutrients to plant which is the fundamental of life and nourish the flora and fauna. Therefore, C balance in the atmosphere is the good indicator for sustainable environment and healthy ecosystem process. SOC varies significantly depending upon the biomass contents, vegetation cover, rate of disintegration, as well as soil structure and parent materials. As per the soil order, the SOC pool varies significantly across the world's soil (Fig. 2).

C input through photosynthesis and its losses through respiration can maintain C balance in our environment where we exist. Moreover, belowground soil mass is the storehouse of various soil-inhabiting organisms like earthworm, protozoan, fungi, insects, faunal mass, and other microbes. These organisms decompose and disintegrate extensive root systems of plants and produce humus as long live storing SOC (Fig. 3). Moreover, SOC distribution can vary as per locality, soil type, and prevailing climatic conditions (Singh et al. 2014). The prevailing climate regime such as temperature and rainfall can influence the dynamics of SOC (Deb et al. 2015; Kumar et al. 2018). For example, rising temperature may increase inputs of C in the soil through increasing plant production along with increasing populations of decomposing microbes (Keestrea et al. 2016) which disintegrate SOC and promote net loss of C and release in the atmosphere (Crowther et al. 2016).

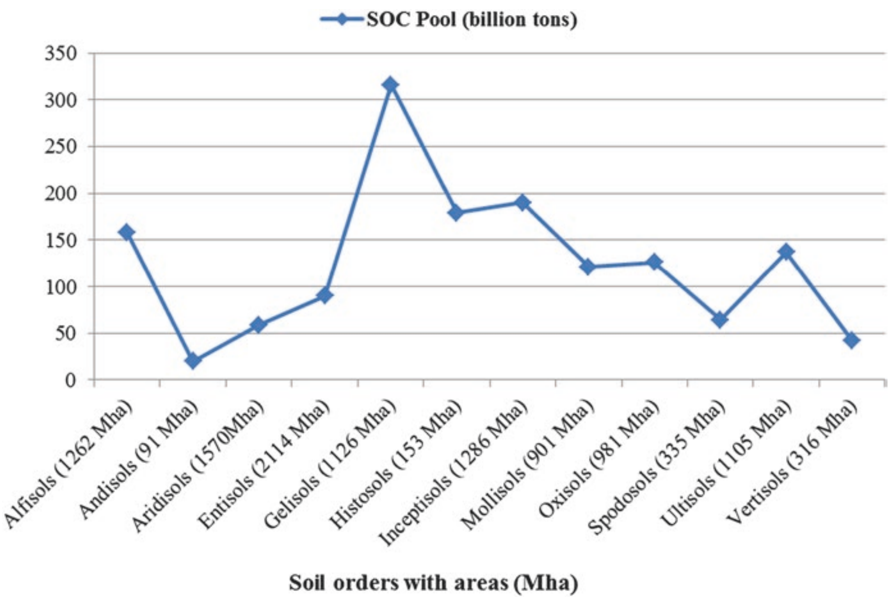

Fig. 2 SOC pools in different orders of the world soils. (Eswaran et al. 2000)

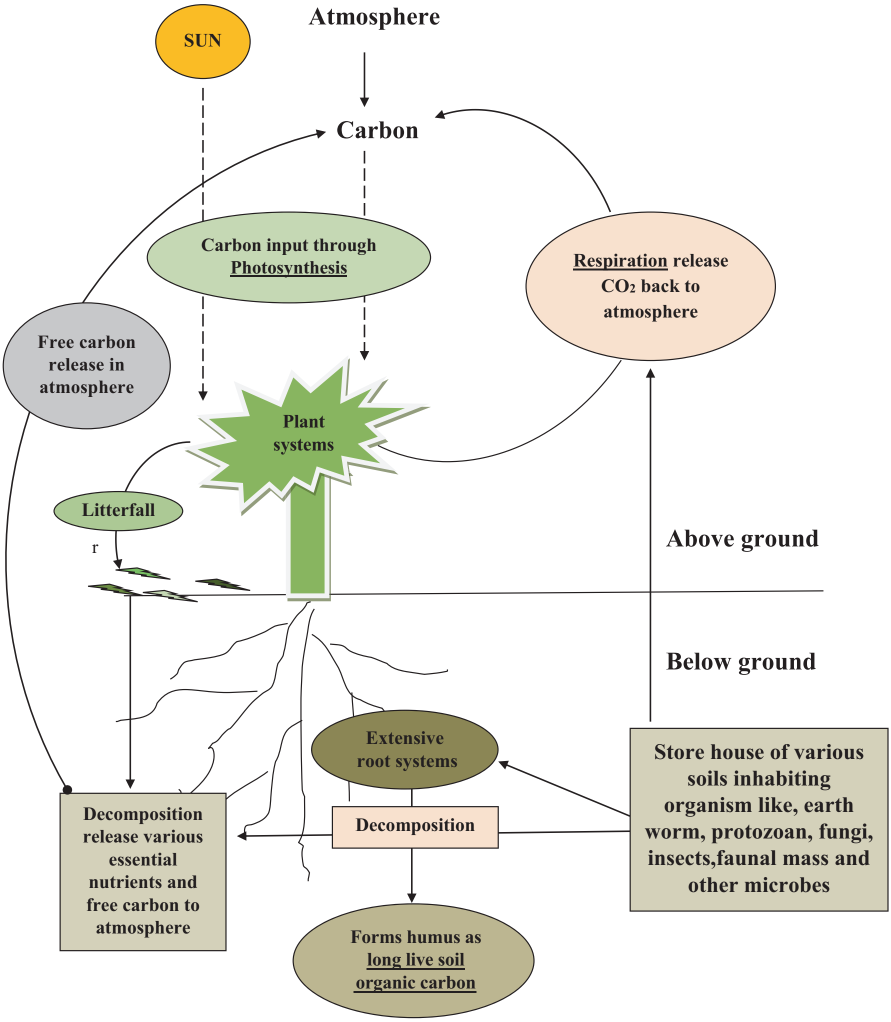

Fig. 3 Carbon balance for healthy ecosystem. (Keestrea et al. 2016; Crowther et al. 2016)

5 Soil: Source of Essential Elements

Soil stores essential elements for the metabolism of plants and animals which is the basis of proper functioning of ecosystems and efficient biogeochemical cycling. Nitrogen (N), phosphorus, and potassium represent major essential elements rather than minor elements such as iron, manganese, copper, zinc, sulfur, calcium, magnesium, molybdenum, boron, etc. These all elements are found in both organic and inorganic form. *The major question is how these all essential elements are prevalent in soils?*

The presence of essential nutrients in soil depends on the history and origin of rock minerals from where soils are formed. Also nature and type of rock, their weathering, type of minerals, etc. can release different types of nutrients in soil solution. Similarly, existing plants and vegetations and type, nature, and process of successions can influence the presence of essential elements in that soils. As we know, plant needs 17 essential nutrients for their metabolic (catabolism + anabolism) processes and proper growth (Troeh and Thompson 1993), of which 3 life-sustaining essential elements like C, hydrogen, and oxygen are available through both water and air rather than other 14 elements which are available through applications of manures and organic and inorganic fertilizers and from other sources (Parikh and James 2012). They take up these essential nutrients through their extensive root systems and store into the body part as in leaves. In turn, leaf and litter falls and their decompositions release various types of essential elements in soils, and this can maintain the fertility status along with health status of soils (Jhariya 2017b; Verma et al. 2015).

6 Soil: An Interlinkage Between Human and Ecosystem

There is a great interrelationship between soil, plants, animals, and humans with the entire ecosystem, and this link exists from micro to macro level. This linking concept makes nexus among them for proper functioning of ecosystem structure and functions. A model has been developed (Fig. 4) which shows synergies among soil health and productivity to animals and human well-being. Besides mitigating

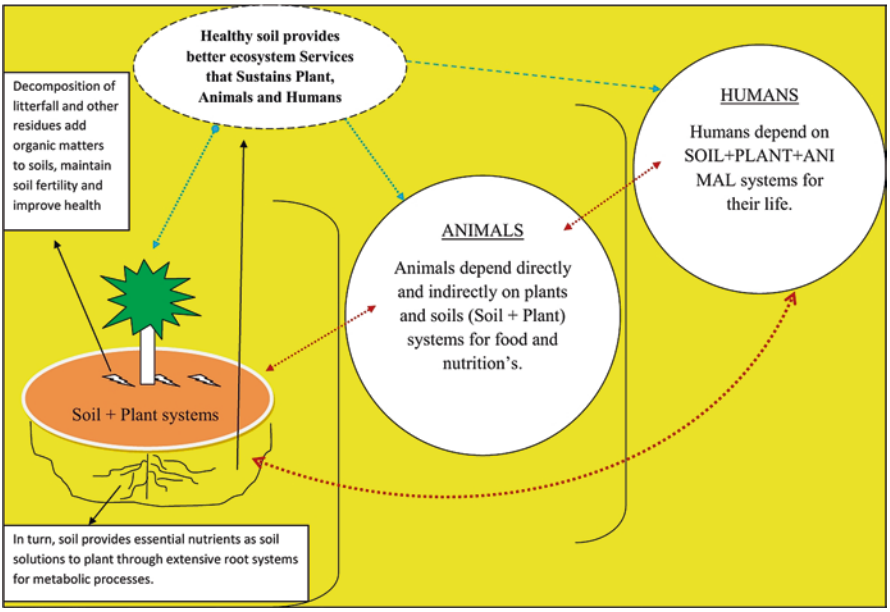

Fig. 4 Linking concepts between soil, plants, animals, and human being. (Singh et al. 2017)

flood and work as a substratum for the plant communities, soil is prerequisite for the provision of greater services to humans (Daily et al. 1997; Andrews et al. 2004; Wall et al. 2004).

Healthy soil gives better ecosystem services which give both direct and indirect benefits to all organisms including humans for sustaining their lives. MEA (Millennium Ecosystem Assessment) classified various forms of ecosystem services which deliver both tangible and intangible benefits to humans, of whom intangible benefits can be quantified and measured by rates or per unit time (Robinson et al. 2012; Meena et al. 2015).

7 Soil as the Building Block of Ecosystem

Soil supports and nurtures the entire ecosystem such as various terrestrial ecosystems in the form of cultivated agricultural land and forest biomes, agroforestry, humans, livestock, and inhabiting microorganism.

7.1 Soil for Agriculture

Soil is one of the important substrates for agricultural crops that stores essential nutrients, billions of microorganisms, and variety of fauna which play an important role in the functioning of soil ecosystem services along with productivity and profitability enhancement. As we know, healthiest soils produce more healthiest and nutritive (qualitative) foods along with more and diverse productivity (quantitative) which can meet out the challenges of hunger of billions. Healthy soil results better environment which is the foundation of higher agricultural productivity and profitability to poor farmers. Thus, there is interlinkage among soil health, environment quality, and sustainable agricultural productions (Fig. 5). Therefore, soil health and quality are the pillars of agricultural sustainability through better air, water, and soil management to maintain environmental quality which can enhance socioeconomic and health objective of poor farmers and build FNS (Brevik 2009).

7.2 Soil for Forestry

Forest is world air conditioner and its type varies as per climate and soil. A characteristic of world forest and its C content is depicted in Table 1 where tropical forest contributes 553 Pg (340 in plant and 213 in soil) followed by boreal forests 395 Pg (57 in plant and 318 in soil) and temperate forest biomes 292 Pg (139 in plant and 153 in soil) (Prentice 2001). Also region-wise C storage value of soil vs vegetations is depicted in Table 2 where Russia shows maximum ratio (3.38) that indicates soil stored more C than vegetations in this region (Dixon et al. 1994).

Several authors have concluded that the occurrence of C varies according to variation in latitudes. For example, around 37, 14, and 49% of the total value (1240 PgC)

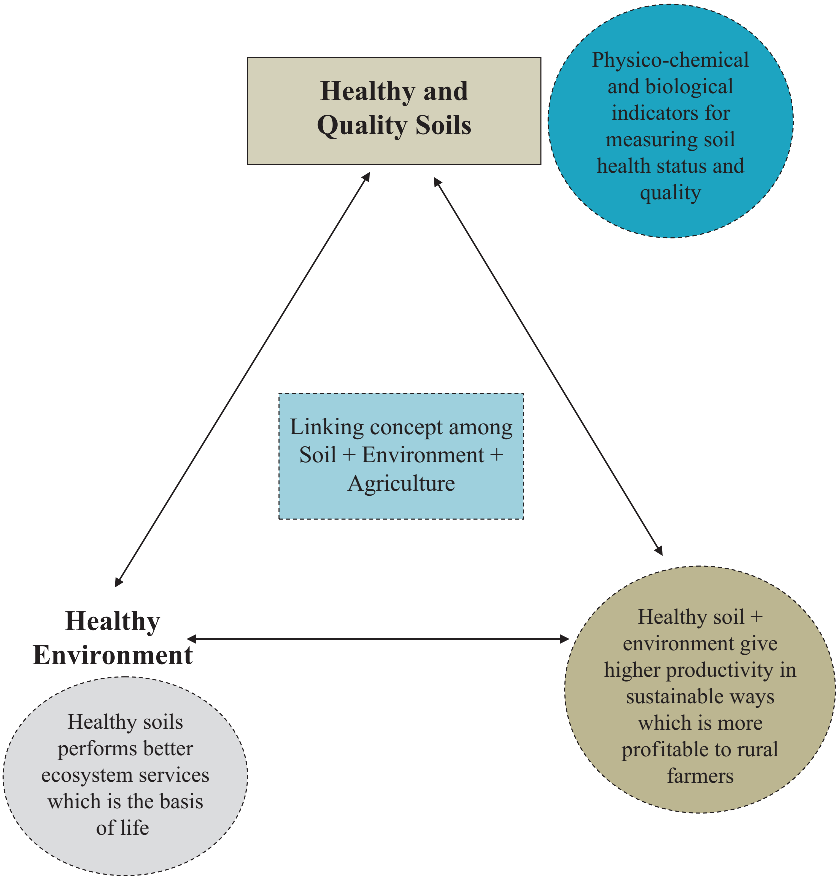

Fig. 5 Triangle model from soil to agricultural sustainability: a linking concept. (Usman and Kundiri 2016; Kibblewhite et al. 2008; White et al. 2014)

of C in both forest and soils are concentrated in forests of low, mid, and high latitudinal region. Similarly, SOC varies as per forest type as boreal forest contributes 85% SOC of terrestrial C stock followed by both temperate and tropical rainforests (60 and 50% of terrestrial C stocks). The regions of tundra, taiga, and pre-tundra represent higher quantity of SOC stocks. Also, the stock of OC in forest soils ranges from 0% to 50% in young to wetland soils (Lal 2005; Ashoka et al. 2017). Therefore, soil is the important substratum for the growth and productivity of forests or woodland.

Soil provides a base to grow and sustain the life of forest through nutrient cycling and availability of various essential elements. As we know, soil provides supports, nutrients, and water to vegetation pools, and in turn, forest helps in creation and formation of new soils through addition of litter and foliage, its decomposition, and nutrient release process (Jhariya 2017b). Thus, soil and forest are intrinsically linked with each other, and these resources can mitigate the changing climate through storage and sequestration of atmospheric C which helps in maintaining environmental security along efficient ecosystem services (Fig. 6).

Table 1 Characteristics of world forest and carbon content

Forest biomes	Characteristics	Total carbon storage value (Pg)	Relative percentage contribution
Tropical forest (1.76 Mha area)	Also called the lung of the world. Area comes between tropic of cancer and tropic of capricorn. Distributed in Latin America, Indo Malaya, and some part of African continent. High humidity along with rainfall (throughout the year) gives luxuriant type of vegetations. Presence of evergreen tree, buttress, liana, abundant undergrowth are the peculiar characteristic along with high biodiversity	553 Pg (340 in plant and 213 in soil)	Plant contributes 61.48% carbon than soil having 38.52%
Temperate forest (1.04 Mha area)	Distributed in northern and southern hemisphere, moderate type of temperature and rainfall, comparatively less diversity of trees and undergrowth than tropical forest. Trees are deciduous in nature, and emergence of new leaves followed by shedding of old leaves throughout the years. Important trees are oak, ash, beech, redwood, etc.	292 Pg (139 in plant and 153 in soil)	Plant contributes 47.60% carbon than soil having 52.40%
Boreal forest (1.37 Mha area)	Distributed in subarctic and cold climate of the world such as Canada, Alaska, Finland, China, Indonesia, the USA, some part of Russia, etc. Severe and long winters along with very low temperature, i.e., cold climate and short period of summer/hot. Vegetation having close canopy and needle type of leaf. Pine and larch forest are common in this biome	395 Pg (57 in plant and 318 in soil)	Plant contributes 14.43% carbon than soil having 85.87%

Modified from Prentice (2001)

Table 2 Region-wise relative abundance of carbon in soil vs vegetations (Dixon et al. 1994)

Area	Relative carbon content ratio in soil vs vegetation (soil carbon/vegetation carbon)
China	1.19
Russia	3.38
USA	1.74
Australia	1.84
Asia	1.05
Africa	1.21

7.3 Soil for Agroforestry

Besides agriculture and forest, soil is the intrinsic component and supports the growth of various agroforestry systems, and in turn, agroforestry maintains soil health and quality through the process of close and efficient nutrient cycling (rather than open type of nutrient cycling in sole plantation) through addition of variable OM and its decomposition through diverse microorganism which can release

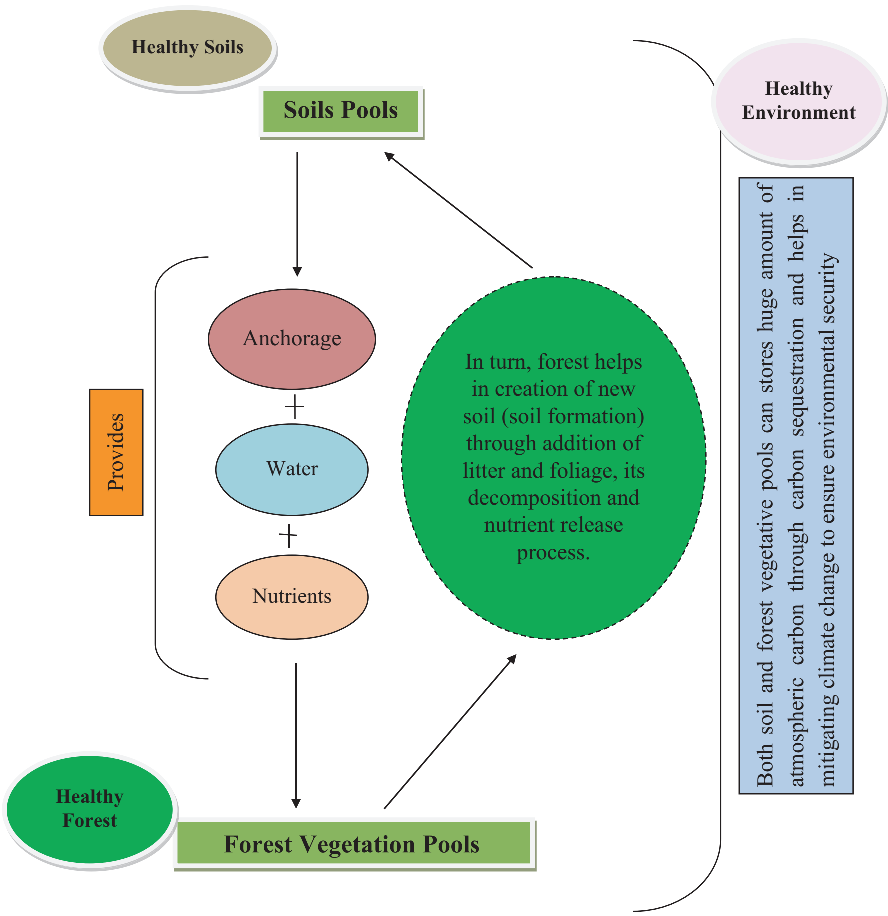

Fig. 6 Linking model between soil pool and forest vegetation pools. (Lal 2005, 2008)

various essential elements into the soil. Agroforestry is a location-specific intrinsic model comprising three elements such as tree, crop, and livestock on a single piece of land, provides multifaceted outputs along with tangible (direct benefits as timber and non-timber forest products) and intangible benefit (indirect benefits as soil-water conservation, efficient biogeochemical cycle, watershed management and pollution control, etc.) (Jhariya et al. 2015; Singh and Jhariya 2016).

Similarly N-fixing multipurpose trees in agroforestry can make N available in soil which is readily mobilized to plant through extensive root systems and enhance the productivity of both soil and crops. For example, *Acacia nilotica* (babool) as N-fixing tree in agroforestry systems performs multifarious functions through enhancement of soil productivity and gum production (as non-wood forest products) (Raj 2015; Jhariya et al. 2015; Raj and Singh 2017). This will not only improve

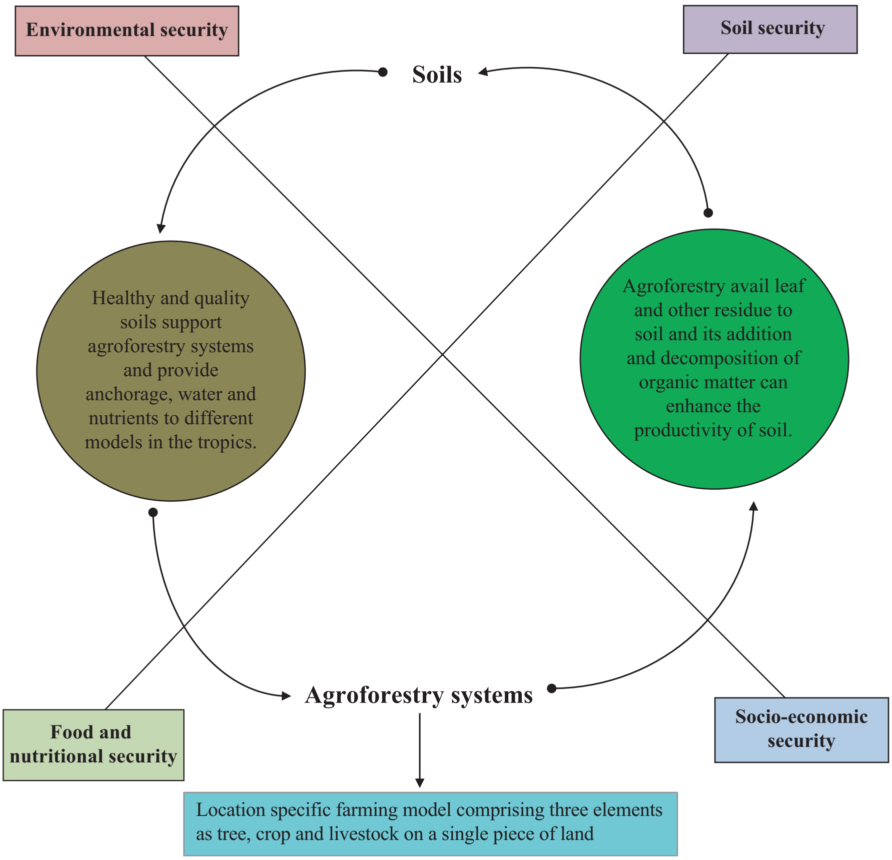

Fig. 7 Intrinsic relationship between soil and agroforestry systems. (Pinho et al. 2012)

soil health status, but augmenting gum production can strengthen socioeconomic status of farmers. Also, addition of leaf and litter fall to soils and its decomposition by various microorganisms can make availability of essential nutrients for betterment of soil and plants as well. Thus, an intrinsic relationship between soil and agroforestry is depicted in Fig. 7.

7.4 Soil for Human

As we know, soil represents a largest pool on the earth and foremost for the existence of biodiversity and ecosystem processes. Soil delivers food-based ecosystem services to human in terms of percentage share of 78% through consumption from direct crops grown on soil and 20% share by indirect source of food, i.e., rather than soil-based food systems (Brevik 2013). *The major question of today is how soil influences the life and health of the humans on earth*? As we know, soil works as invisible hero as from water availability to water purification, litter decomposition to nutrient availability, and food production to availability to human for healthy society along with food, nutrient, and climate security. Soil feeds not only to crops and animals but human also. Healthy soil is the basis of quality and nutritious food, which in turn gives healthy lifestyle to human being.

Degradation of soils leads to some disaster like famine which affects the human life and their survival becomes difficult. Human knows the importance of soil and its role in environmental sustainability processes. Similarly food security is strongly linked with human health system, and well-developed quality soils include good structure, physicochemical properties, and sufficient content of OM pools in soils affecting productivity and food production systems that helps to maintain the supply of food to people in sustainable way (Reicosky et al. 2011; Brevik 2009). Also soil supports different farming systems and helps in quality and nutritious food production which leads to healthy human system and sustainable environment. In other side, unhealthy and poor soils store various toxic elements, heavy metals, industrial toxins, and agricultural-based chemicals (Hubert et al. 2010; Brevik 2009; Banerjee et al. 2018; Yadav et al. 2017b) which can enter food chain resulting into unhealthy and un-nutritious foods for human being (Fig. 8). Thus, healthy and quality soil is the basis of quality human life.

7.5 Soil for Livestock

Besides human life, soil supports animal life too. Soil is the essential foundation for both livestock and wild animals. It helps to provide various essential nutrients through edible grasses/pasture to livestock. Healthy soil is the basis of healthy livestock and healthy environment. Therefore, soil management is important for both grass and pasture management which is the prime feed for livestock. In turn better managed pasture can enhance the ground cover along with fertility of land. Further, livestock manure adds more fertility to the soil through the release of essential nutrients (Fig. 9). Thus, the availability of quality fodder and grasses to livestock for feeding purpose can enhance the productions of high-quality manures which are very essential for soil health and quality enhancement (Muyekho et al. 2000). Also livestock excreta perform a leading role in efficient nutrient cycling processes along with addition of essentials nutrients to enhance fertility status of soil and show the concept of soil nutrient balance in terrestrial ecosystems (Sheldrick et al. 2002). Thus, soil improvement through addition of animal excreta depends on the type of animals, their feeding habitat, diet, weight, nature and characteristics of excreta, etc. (Lander et al. 1998). Therefore, production and availability of excreta from livestock can be utilized as manure, and its production depends on feeding habit and its quality. Also, cereals, oil cakes, oilseeds, crop residues, etc. are important type of concentrated feed for livestock (de Haan et al. 1998).

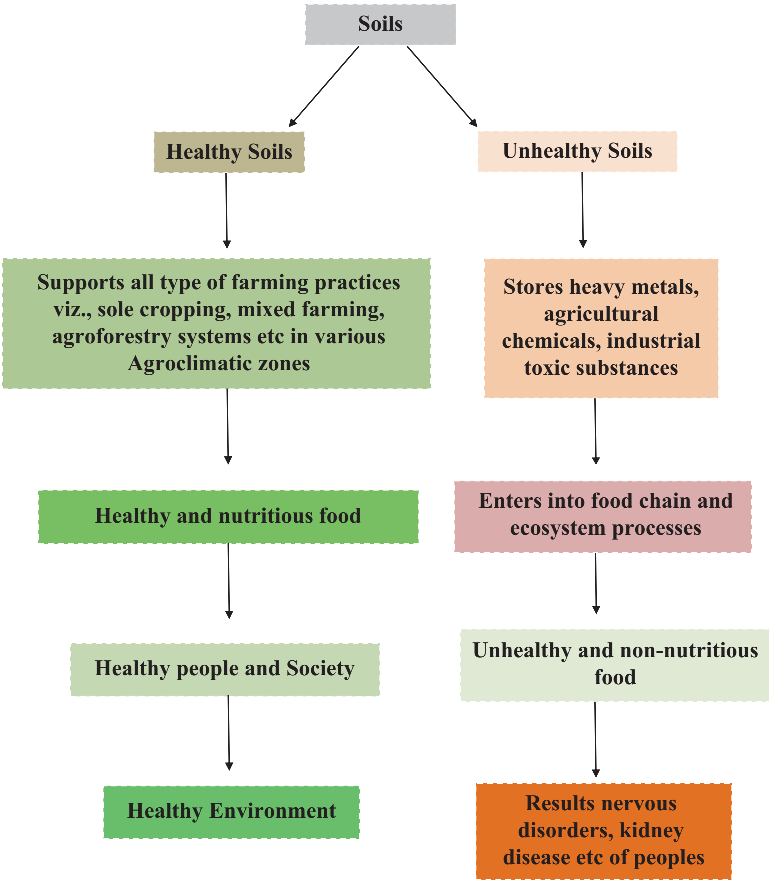

Fig. 8 Nexus between soil and human health. (Nieder et al. 2018)

7.6 Soil for Micro- and Macroorganism

Soil acts as source of essential nutrients as well as harbors a great diversity of inhabiting organism such as bacteria, fungi, protozoa, earthworms, and other animals performing diverse ecosystem processes (Muller et al. 2016). One spoon soil holds billions of bacteria, fungi, protozoa, etc. This microorganism feeds upon dead organic substance and releases essential elements through disintegration and decomposition of OM which reflects the fertility status of soil along with land productivity. Moreover, *Rhizobium* (found in root nodules of Leguminosae plants) bacteria can fix N from atmosphere, and plants get it in available form through the process of N fixation which helps toward increasing soil N pool leading toward soil sustainability (Jhariya et al. 2018b; Datta et al. 2017).

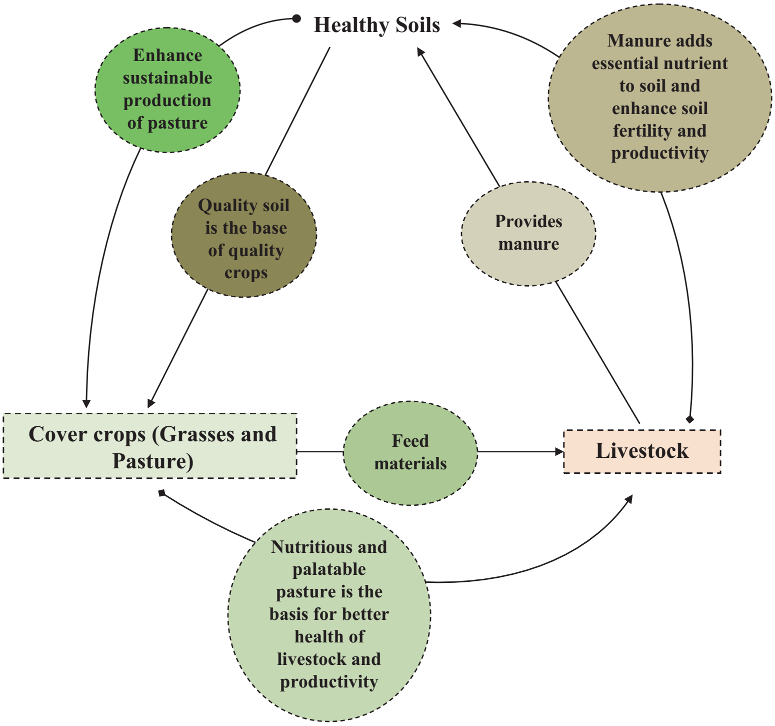

Fig. 9 Triangle models of soil health and livestock. (Muyekho et al. 2000; Sheldrick et al. 2002)

Similarly, mycorrhizal fungi make an intrinsic relationship with roots of higher plants and enhance absorptive capacity of roots for several nutrients from the soil. Besides it, the other organisms like protozoa, nematodes, and earthworms contribute a major portion in both disintegration of OM and maintenance in soil fertility. Earthworms make channel and burrow in soils that enhance the aeration, providing proper space for root proliferation and mix-up of soil mineral to OM (humus). Thus, both microbial diversity and functions is the important base for soil health and fertility (Fig. 10). Numbers of studies have been done on role of microorganisms in promotion of plant growth through better availability of essential nutrients to plants, repellent activity of infectious pathogens in soil, and operating activity and control over hormonal signaling in crops (Verbon and Liberman 2016).

7.7 Soil for Food Security

Healthy soil maintains fertility of soils that enhance the productivity of crop through better climate and water productivity. Soil absorbs and retains atmospheric carbon dioxide (CO_2) in the form of soil OC which helps to mitigate the global warming and enhances the productivity under changing climate which results in provision of

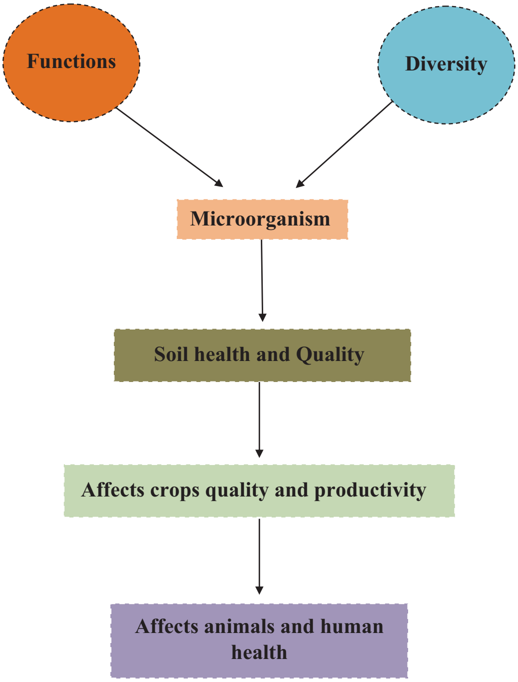

Fig. 10 Triangle models of soil health and microbes. (Muller et al. 2016; Verbon and Liberman 2016)

sufficient food to billions along with FNS program. Moreover healthy soil provides essential nutrients and supply of water to plants resulting availability of optimum water to plants that leads to high productivity and profitability (to farmers). Thus healthy soils interrelate high productivity, profitability, and FNS along with environmental sustainability program (Fig. 11).

It is very interesting to know about SOC and its potential role in enhancing both soil fertility and food security by development of soil health and quality which promote high productivity and yields of crop. An increase in SOC can facilitate nutrient availability and plays an inevitable role in agriculture productions. Moreover, SOC plays inevitable role in yield and productivity enhancement for the farmers who suffer from the shortage of availability of fertilizer and proper irrigation (Lal 2004a) along with enhancement of yield of various crops like wheat (*Triticum aestivum*), maize (*Zea mays*), and cowpea (*Vigna unguiculata*) through rehabilitation of degraded cropland through addition of 1 ton SOC. Also, retaining and conservation of SOC-based agricultural systems can potentially enhance the food production by 17.6 Mt./year (De MoraesSa et al. 2017; Varma et al. 2017). Moreover, some natural and anthropogenic factors result in landslides, erosion problems of both water and soil, and loss of soil C and biodiversity (micro- and macroorganism) which can affect food security along with unsustainable ecosystem processes (Oldeman 1998). Thus sustainability in soil health and productivity are the prerequisite for both food and environmental security along with better ecosystem services.

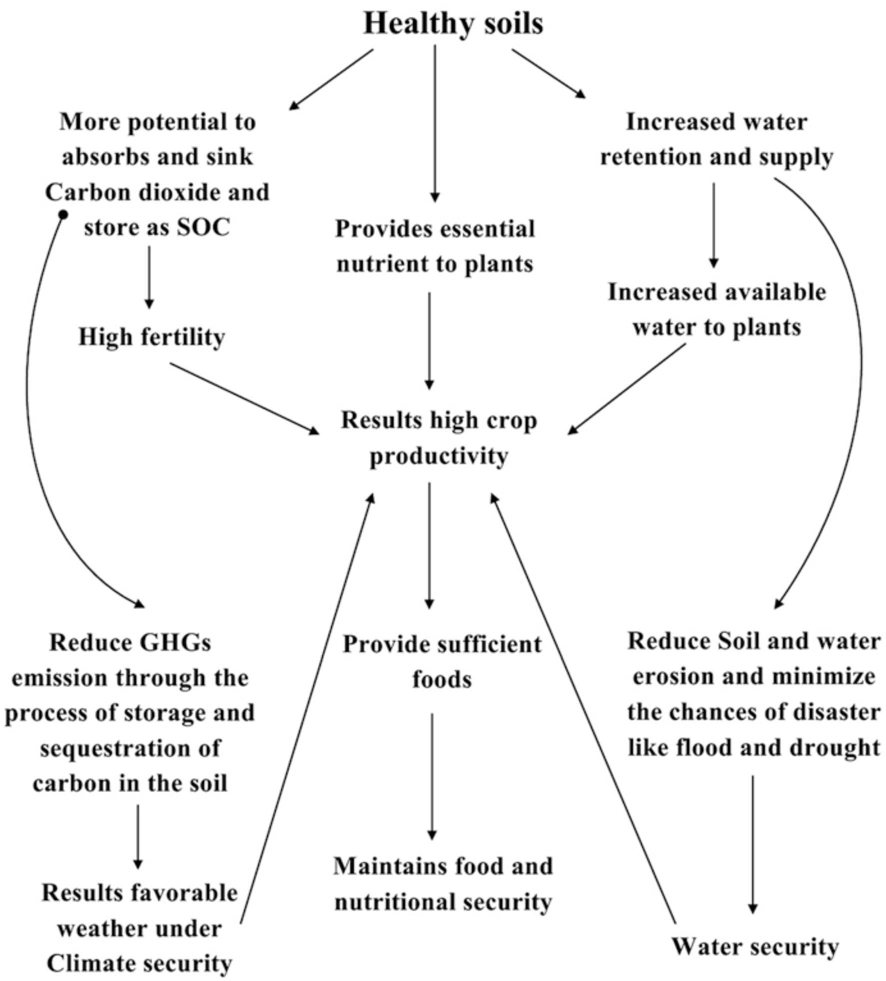

Fig. 11 Linking model between healthy soils and FNS through environmental sustainability. (De MoraesSa et al. 2017; Rojas et al. 2016)

7.8 Soil for Ecosystem Services Provision

Since time immemorial, living organism has been utilized as goods and services from the processes of ecosystem which is shown to be very lucrative for humankind. But the major questions are *how different category and types of ecosystem services exist and grouped?* This is answered by MEA in 2005, and according to them, ecosystem services have four components, namely, regulating, provisioning, cultural, and supporting services (Fig. 12) (MEA 2005) and give overall national security program through delivering water, energy, climate, food, and environmental security (Fig. 13).

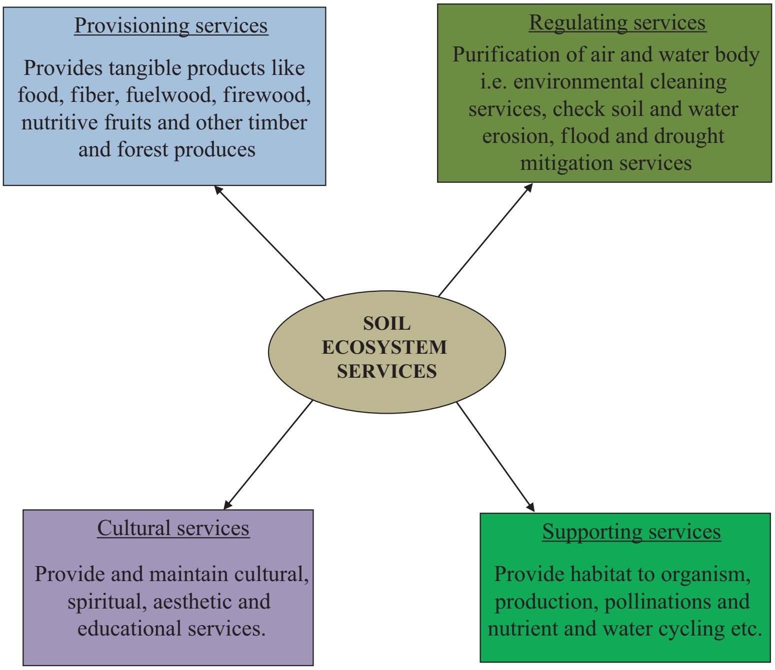

Fig. 12 Soil ecosystem services. (MEA 2005)

Soil is a good medium to support living organism and plays a crucial role in ecosystem services. Soil provides both direct and indirect benefits to organism which resides in the environment. Soil supplies, purifies, and filters the water and plays a major role in water cycling, which stores essential elements in the various forms that can be utilized by plants as soil solution. Soil harbors variety of organisms and provides organic residue for decomposition by various microorganism to release essential elements for sustaining the life of flora on which faunal community depends. However, very little studies and information have been reported in relation to interlinking concept between properties of soil and their ecosystem services. Soil properties reflect their quality and health which are the basis for provision of ecosystem services. Thus, soil ecosystem services depend on the nature, type, properties, and management aspect of soil which can't be deniable at any circumstances (Lal 2009; Meena et al. 2017).

8 Soil: Solution to Climate Change

Soil ranks the third largest sink of C and regarded as very good natural resource. Well-managed soils through optimum growing stocks and soil-inhabiting macro- and microorganism play an important role in management and conservation of soil resources. It is therefore a good strategy for solutions of global warming and changing climate through feasible storage of atmospheric C in both woody vegetation and

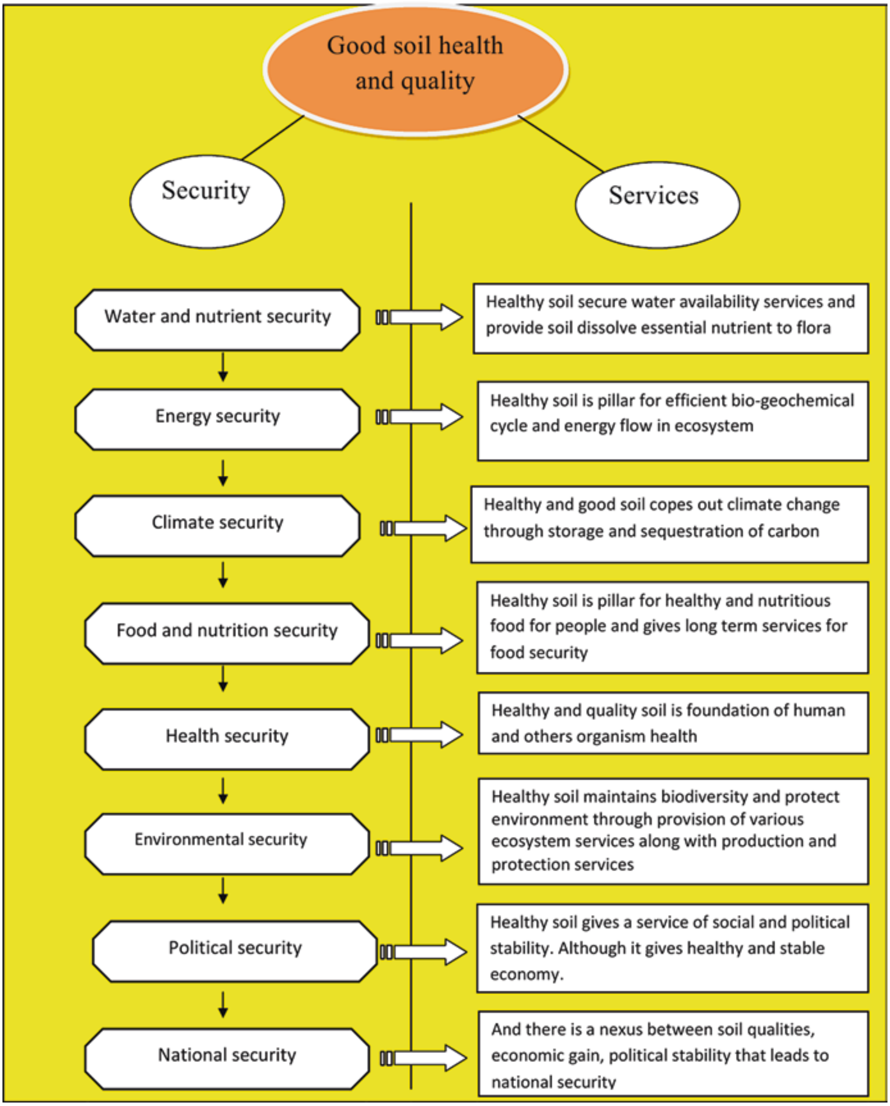

Fig. 13 Soil provision for ecosystem services and national security. (Zhu and Meharg 2015)

soils. Thus, soil helps to combat climate change problem along with environment and ecosystem security.

8.1 Soil as Sink for C Sequestration

As we know, C exists in various forms like atmospheric C, SOC, etc. but is chiefly found in the form of living biomass and provides life on earth. Continuous removal of excess C from land and its presence in atmosphere resulted into an increase in temperature of earth known as global warming. In this context, absorption and storage of atmospheric C in ocean, land, soils, and living organism can mitigate this changing climate and protect our mother earth from excess temperature. Soil is the good sink for C, i.e., pulled out atmospheric C and stores in both above and below ground as C mass. Majorly soil can store C as soil OM for long periods and can be emitted back to the atmosphere. Thus, soil for higher potential of C storage can not only reduce the atmospheric C but also significantly enhances availability of C in soils. Several practices like adoption of conservation agriculture, agroforestry, efficient agronomic practices, cover cropping practices, crop rotation, mixed cropping, integrated nutrient and pest management, aerobic rice cultivation instead of flooded rice, etc. can potentially enhanced the sequestration capacity of C along with less emission of GHGs (greenhouse gases). Among all, the practice of agroforestry helps in conserving soil through storage and sequestration of C in both tree and soil systems. Therefore, C sink capacity of soil in different types of agroforestry systems in different areas is depicted in Table 3. Moreover, both organic and inorganic pools of C (1550 Pg and 950 Pg) in 1 m depth of soil represent soils as the third largest sink of C globally (Lal 2004a).

Similarly, agriculture has two faces: the first represents better practices of agriculture enhancing efficient storage and sequestration of C in soils by 0.4–1.2 Gt/annum (Lal 2004a) and second agriculture itself contributes in the production of CO_2 which is major GHGs along with methane and nitrous oxide to atmosphere by faulty land conversion systems, faulty management practices, etc. Therefore, good and efficient management of agriculture practices not only check several environmental problems but also benefits in terms of enhancing soil OC by 10% sequestration of overall emission (approximately from 8 to 10 gigaton per year) (Hansen et al. 2013). Thus, several farming practices and adoption of agriculture systems reflect stabilization and destabilization of C which can affect rate of storage and sequestration of C and its emission in atmosphere (Fig. 14).

Good farming practices obviously enhance C sink capacity of soil which can store soil OC for long term and reverse can release C in atmosphere which is a prime concern today due to rise in temperature as global warming. As we know, the presence of plant residue such as branch, leaf, shoot, husks, twig, etc. adds more biomass to soils and stabilizes as soil OC for long term and minimizes the atmospheric emission of C. Thus, addition of plant residues along with efficient agronomic practices such as optimum use of green manure, FYM and recommended dose of fertilizers can potentially enhance the soil OC content (Chaudhury et al. 2016). Further, the practices of conservation tillage can enhance the sequestration value of C and increase soil C pools with minimizing CO_2 emission in the atmosphere (Dean and Kataki 2003; Lal 2004b; Baker et al. 2007; Yadav et al. 2017).

8.2 Soil Organism for C Sequestration

Soil-inhabiting organisms (particularly microorganism) decompose plant and other organism-based OM and release C as CO_2 in the atmosphere through heterotrophic respiration of microbes. Meanwhile, some C (as organic and inorganic type) is left for further decomposition and somehow stored and sequestered in soil. Thus the

Table 3 Different agroforestry systems and its carbon absorption values in the world

Agroforestry practices in region	C sink value of soil	Reported author
Gmelina (khamar) based on agrisilviculture systems in Chhattisgarh, India	27.4 Mg ha^{-1}	Swamy and Puri (2005)
Homegardens system in Panama	45–2.3 Mg ha^{-1}	Kirby and Potvin (2007)
Homegardens system in Africa	Up to 200 Mg ha^{-1}	Nair (2012)
Cut and carry practices under silvopastoral systems in Africa	1.5–3.5 Mg ha^{-1}	
Trees system on pastureland and grazing area in silvopastoral systems in Africa	60.0 Mg ha^{-1}	
Tree species like poplar (*Populus* spp.) along with field crops such as wheat, maize, and soybean (*Glycine max*) under hedgerow cropping system in Canada	1.25 Mg ha^{-1}	Oelbermann et al. (2006)
Tree species like *Pinus elliottii* (slash pine) along with the pasture (*Paspalum notatum*) under silvopastoral systems in Florida, USA	6.9–24.2 Mg ha^{-1}	Haile et al. (2008)
Mixed tree stands system in Puerto Rico		
Combination of *Eucalyptus* species with *Casuarina equisetifolia* (beach oak)	61.9 Mg ha^{-1}	Parrotta (1999)
Combination of beach oak tree species with *Leucaena leucocephala* (Subabul)	56.6 Mg ha^{-1}	
Combination of eucalyptus species with Subabul	61.7 Mg ha^{-1}	
Quercus suber (cork oak) based on silvopastoral systems in central Spain region	26.5–50.2 Mg ha^{-1}	Howlett (2009)
Betula pendula (silver birch) based on silvopastoral systems in northwestern Spain region	133–150 Mg/hectare	Howlett et al. (2011)
Tree species like *Eucalyptus* with *Brachiaria* species in Brazil	353 Mg/hectare	Tonucci et al. (2011)
Silvopastoral system in Florida, USA	512 Mg/hectare	Haile et al. (2010)
Poplar intercropping based on alley cropping systems in Guelph, Ontario, Canada	57 Mg/hectare	Bambrick et al. (2010)
Poplar based on agrisilviculture system in Punjab, India	9.4 Megagram carbon ha^{-1} $year^{-1}$	Chauhan et al. (2010)
Subabul based on agrisilviculture system in Andhra Pradesh, India	2.77 Megagram carbon ha^{-1} $year^{-1}$	Rao et al. (1991)
Tree species like babool in silvopastoral systems in Haryana, India	2.81 Megagram carbon ha^{-1} $year^{-1}$	Kaur et al. (2002)
Mixed tree species under kitchen gardens system in Kerala, India	1.60 Megagram carbon ha^{-1} $year^{-1}$	Saha et al. (2009)
Tree species like beach oak based on agrisilviculture system in Tamil Nadu, India	1.57 Megagram carbon ha^{-1} $year^{-1}$	Viswanath et al. (2004)

(continued)

Table 3 (continued)

Agroforestry practices in region	C sink value of soil	Reported author
Fodder species like *Brachiaria brizantha* (bread grass) intercropped with *Cordia alliodora* (Spanish elm) and *Guazuma ulmifolia* (West Indian elm) based silvopastoral system practiced in the Costa Rica	132 Mg ha^{-1}	Amezquita et al. (2005)
Forage plant like *Arachis pintoi* (pinto peanut) intercropped with *Acacia mangium* (mangium) tree in silvopastoral system in Costa Rica	173 Mg ha^{-1}	
Poplar-based intercropping of *Hordeum vulgare* (barley) in Canada	78.5 Megagram/hectare	Peichl et al. (2006)
Tree species like *Pseudotsuga menziesii* (Douglas fir) with *Trifolium subterraneum* (subterranean clover) in the USA	96.0 Mg ha^{-1}	Sharrow and Ismail (2004)
Leucaena-based hedgerow intercropping in West Nigeria, Africa	13.6 Mg ha^{-1}	Lal (2005)
Fodder bank system comprises various species such as *Pterocarpus lucens* (small-leaved bloodwood), *Gliricidia sepium* (Mexican lilac), and *Pterocarpus erinaceus* (African rosewood) in Mali	33.4 Megagram/hectare	Takimoto et al. (2008)
Crop like maize with Mexican lilac in Malawi	123 Mg ha^{-1}	Makumba et al. (2007)

accumulation of residual organic material represents a huge amount of C and N along with other elements in soils (Reynaldo et al. 2012). Further exceeding value of C in soils through higher value of photosynthetic C over respiration loss of C by microbes reflects net C sequestration value in soils (Lal 2004a; Woodward et al. 2009; Reynaldo et al. 2012). Therefore, the extent and potential of C sequestration of soil are generally dependent on the type and nature of both soil and soil-inhabiting microbial communities along with prevailing climate. For example, associated ratio of two microorganisms such as fungi to bacteria in soil reflects potential of soil C sequestration capacity, and its dominancy in soil can be predicted by pH value and C:N ratio (Helgason et al. 2009). Thus, both fungi and bacteria along with other microbial communities in soils represent C flux, storage dynamics, and sequestration value, and its mechanism is depicted in Fig. 15.

8.3 Earthworm and Soil C Storage

Indeed, earthworm performs a vital role in regulation of ecosystem through enhancement in C absorption capacity in soil pool. Various literatures are available on C storage and sequestration capacity of earthworm and their strong effects on C cycling and interaction (may be positive and negative) with other soil-inhabiting organism (Mendes et al. 2013).

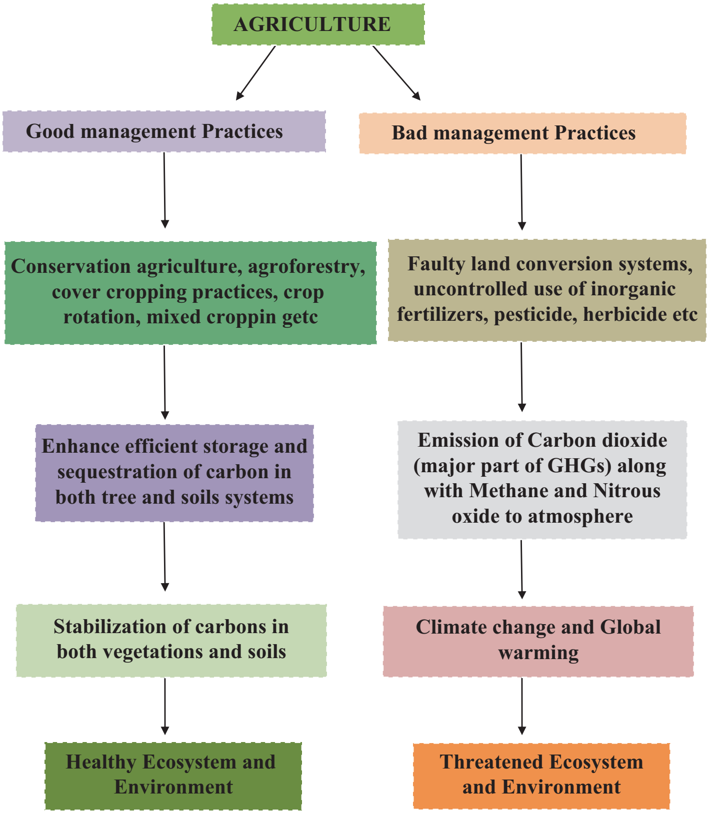

Fig. 14 Farming practices as stabilizing and destabilizing carbon. (Lal 2004a, 2004b; Baker et al. 2007; Goh 2004)

Moreover, various effects have been shown by earthworms such as alteration in physicochemical properties of soil and nutrient cycling (including OC based cycling) and infiltration rate of water and contribute significantly on CO_2 emissions in environment (Eisenhauer 2010; Capowiez et al. 2014). Also, earthworm's interaction with other organism which inhabit both above- and below ground can affect ecosystem functioning and its structure and function (Edwards 2004) particularly forest ecosystem (Fisichelli et al. 2013) in terms of negative impacts as reduction in leaf litter along with removal of OM from uppermost soil that affects population and diversity of plant (Resner et al. 2015; Buragohain et al. 2017).

Earthworm performs burrowing activity which results in enhancement of soil porosity, drainage, and structural properties. Similarly disintegration and digestion of dead and decaying plant and others can release C which can stabilize in soils in both organic and inorganic forms which is highly nutrient rich and helps in augmenting soil fertility and physiochemical properties. Thus the role of earthworm is not confined to only storage and sequestration of C in soil, but it links with overall ecosystem security through betterment of soil health and quality, food and health security, and climate and environmental security (mitigating global warming) (Fig. 16).

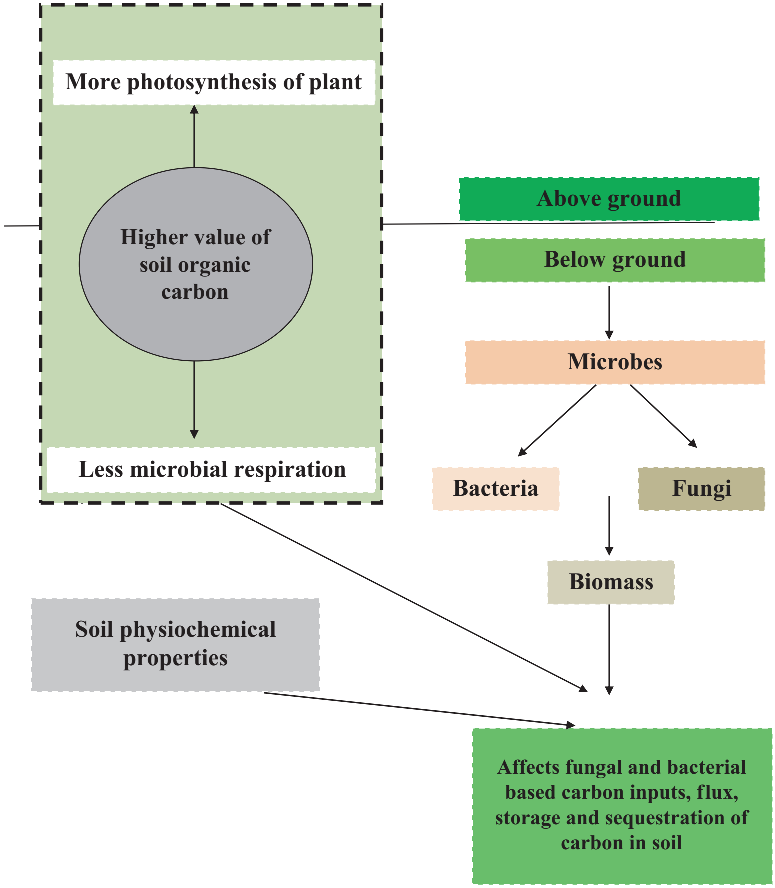

Fig. 15 Mechanism of carbon inputs in soil through microbes. (Gougoulias et al. 2014)

9 Sustainable Soil Management

Faulty land use practices, deforestation, uncontrolled inputs of inorganic fertilizers, low inputs of OM, etc. affect soil health and ensure land degradation. This can be reverted by the adoption of scientific and SSM which helps in maintaining C content in the soil and other essential nutrients along with diverse organism that enhances food productions in more sustainable way. Enhancement in land productivity, conservation of top fertile soil, minimizing erosion, maintaining essential nutrients and population of beneficial microorganism, etc. are the significant effects of SSM practice. *But the major concern is how can we keep this significant effect in sustainable way?* This can be achieved through maintaining the OM content in soils, i.e., SOC, which is the foremost indicator for soil health and quality. Thus, sustainable and scientific management of soils can improve the status of soil fertility through addition of OM (enhance OC pools), improve soil structure and texture

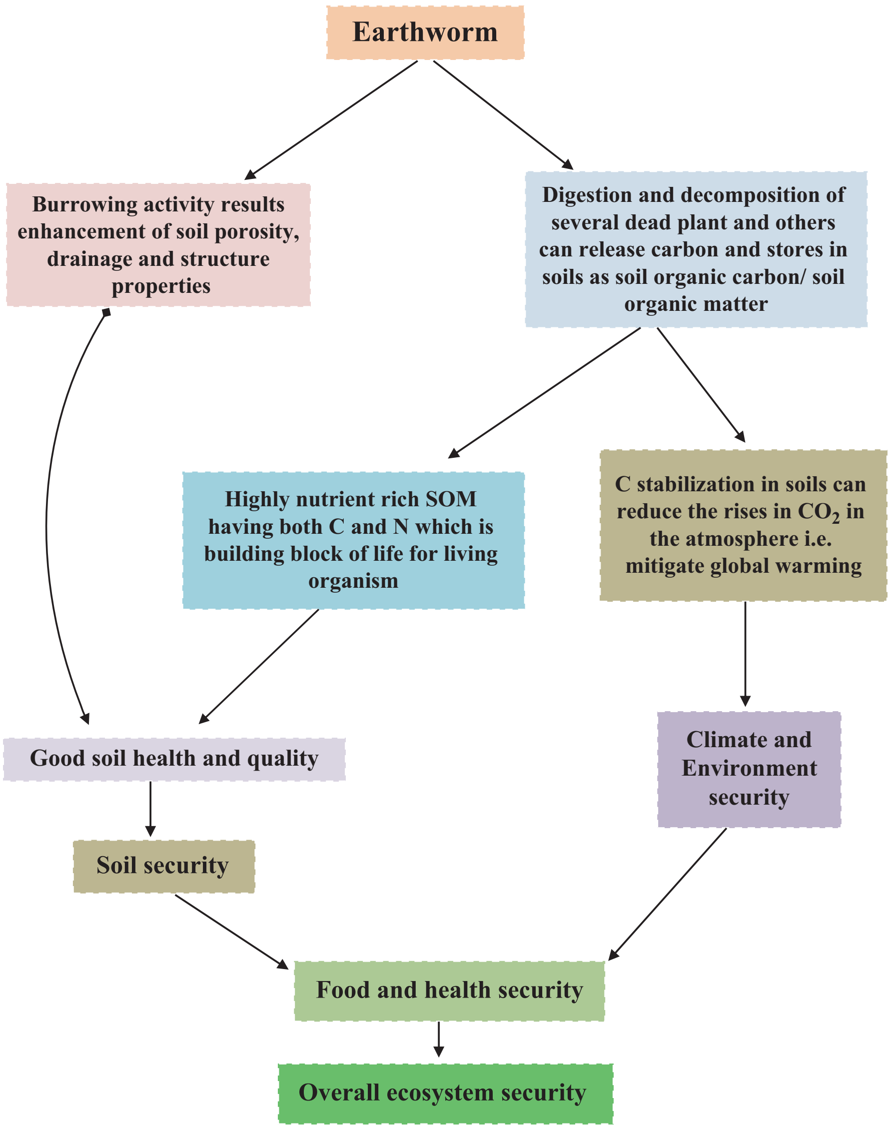

Fig. 16 Earthworm for soil and environment security. (Edwards 2004; Fisichelli et al. 2013; Mendes et al. 2013; Bertrand et al. 2015)

which enhance the water availability (to plant), control soil and water erosion, and regulate the soil temperature which is most important for the existence of several soil-inhabiting organism, etc.

10 Roadmap and Future Strategies for Soil Sustainability

Our future lies upon the soil; therefore soil health is the central concept for the perspectives of production and protection of environment. Soil degradation and deterioration is the major concern today, which affects the flora and fauna along with food and environment security. There is a need of some relevant and scientific research on soil degradation through faulty land use practices, climate change impacts on soil, extent of soil C storage and C sequestration, and interrelations among soil and various organisms which can help in understanding of soil and its link with delivery of several ecosystem services.

Sustainable practices such as use of biofertilizer and vermicompost, organic manuring, green manuring, and mulching activities should be promoted to effectively deal with soil degradation. It is therefore an urgent need of the hour that these policies should be integrated in the sectors of agriculture, forestry, and environment. Soil erosion is also a big challenge in front of soil sustainability. Planting of species having high soil binding capacity should be promoted. Reducing the external inputs of agrochemical in terms of synthetic fertilizers and chemical is also an important policy step to combat the problem of nutrient deficiency, soil fertility, and overall pesticide problems. Efficient recycling of waste materials in terms of compost, FYM not only solves the problem of environmental pollution but simultaneously they will add to the soil C pool.

11 Conclusion

Degradation of soils through both natural and anthropogenic activities is the major concern today which not only declines the productive capacity of land but also affects health status of soil, organism, and whole environment. Soil is being a part of our culture and society, and without it, there is no meaning of life on earth. Soil can hold million tons of C through addition of plant and animal residues and absorption of atmospheric CO_2 through the process of C sequestration which can not only maintain the SOC but can provide a solution for the global problem of climate change which is a major concern today and contributes degradation of environment and ecology. Soil holds all living creature and sustains the life through the provision of various ecosystem services. Moreover, stabilization of C in soil (as SOC) can maintain health status of both soil and soil-inhabiting organism which plays very peculiar role in decomposition, release, and availability of essential nutrients to plants on which animals and people depend. Therefore, in this context, sustainable management of soil can keep the status of OM in soil which is the basis of land productivity that leads to improved fertility and yield capacity of crops to combat the problem of food insecurity. Thus, healthy soils boost the productivity and profitability through soil, food, and environment security and promote sustainability in ecosystem processes.

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Forest as a Sink of Carbon in Global and Nepalese Context

Anup K. C.

Contents

Abstract

Forest plays a great role to absorb carbon dioxide (CO_2) present in the air and store in its floral parts and the soil. The amount it sinks varies according to the time, type of vegetation, geographical area, and the management strategy applied on it. It is an important method of reducing current global climate change problem and increasing ecosystem balance. This chapter is prepared with the help of

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review of researches on carbon stock (CS) and carbon (C) sequestration in the global and Nepalese context. Different methodological issues and findings on CS are documented in this chapter. There are different studies conducted throughout the globe about assessment of CS and C sequestration rate. These studies have used different methodologies for assessing C stored in tree, shrub, dry leaf, herbs, grass, and soil. Most of the researchers have used allometric equations for analyzing C in aboveground biomass, laboratory analysis for soil organic carbon (SOC), and root to shoot ratio for C in belowground biomass. There was variation of CS in its tree; sapling; leaf litter, herbs, and grass (LHG); and soil. Also, it varies across different species and location. But, the amount of C stored by forest was increasing with the passage of time. The average CS around the world is 73 tons per hectare having the highest in South America with 122 tons per hectare and the lowest in Europe with 45 tons per hectare. The average CS in tree component of Nepal is 108.88 tons per hectare, litter and debris is 1.18 tons per hectare, and soil is 66.88 tons per hectare. Management strategy has greater influence on C storage and sequestration. Monetary incentives such as Reducing Emissions from Deforestation and Forest Degradation (REDD) schemes and payment for ecological services to the managers would help to absorb more CO_2 from the atmosphere and reduce the rate of greenhouse gas emission.

Keywords
Carbon sink · Forest · Global and Nepalese context · Methodologies

Abbreviations

ANSAB	Asia Network for Sustainable Agriculture and Bioresources
C	Carbon
CF	Community forest
CO_2	Carbon dioxide
CP	Carbon pool
CS	Carbon stock
DBH	Diameter at breast height
GPS	Global positioning system
ICIMOD	International Centre for Integrated Mountain Development
LHG	Leaf litter, herbs, and grass
Mg	Megagram
m^2	Square meter
REDD	Reducing Emissions from Deforestation and Forest Degradation
ton/ha	Tons per hectare

1 Introduction

Forest is one of the essential natural resources with great potential in absorbing atmospheric carbon dioxide (CO_2) and regulating global climate (Aryal et al. 2013; Bayat et al. 2012; K C et al. 2013a, b; Meena et al. 2018a). Its biological diversity is an outcome of physiochemical, biological, and socioeconomic relationships from the historical time scale (Pandey et al. 2014a, b). Further, it can act as a storehouse of carbon (C) compounds in the form of living biomass and in the form of soil due to high litter composition of vegetation (K C et al. 2013a, b; Jhariya 2014). Leaves, branches, stems, and roots of plants store biomass C in different percentages through the process of photosynthesis and pass its certain portion to the soil (Chen 2006; Ramachandran et al. 2007; Jhariya 2017). In spite of the climate regulation services, forest provides other provisioning, regulatory, supporting, and cultural services (Chaudhary et al. 2015; Jhariya and Yadav 2018).

Forest product usage and its management strategy affect the storage of C in it (Bayat et al. 2012). Dependency on forest products and unsustainable harvesting can increase the use of forest products (Chaudhary et al. 2015). This will decrease the C storage capacity of the forest. There are different types of forest across the world depending upon the management strategy to conserve their floral and faunal biological diversity. There are different categories of forests across the globe depending upon different ranges of climate, vegetation types, soil types, altitudinal range, and other biotic and abiotic factors. This causes different rates of C sequestration throughout the world. According to the ownership of resources, some are owned and managed by the local community and local interest groups, while others are totally protected by the state and other nongovernmental organizations (K C 2017). Community-managed forest in the case of Nepal is successful in reducing rate of deforestation resulting in higher carbon stock (CS) (K C et al. 2018).

As forest had benefit of climate regulation through atmospheric C absorption, it is necessary to observe the CS in different forest types and management strategies across the world. This chapter identifies different methodologies used by researchers for assessing CS across the globe with special focus to Nepal. It shows the status of CS and C sequestration in the global and Nepalese context. Also, it provides information about variation in CS in different vegetative parts of plant.

2 Forest as a Carbon Sink: Global Context

Forest is taken as a cost-effective way to reduce impacts of global change in climate by providing certain incentives to the protectors of the forests (Ullah and Al-Amin 2012). As forest had high potential of absorbing global atmospheric CO_2 in its different life forms (Chen 2006; Jhariya 2017), there is a need of collection of reviews about different researches done throughout the world on potential of forest toward C sequestration. For conserving and managing trees in the forests, C sequestration potential and absorption of atmospheric CO_2 can be a matter of discussion in international forums (Chen 2006). In the case of India, C sequestration from forest and its management is one of the important matters of discussion in the 1st half of the twenty-first century (Ramachandran et al. 2007; Jhariya 2017; Kumar et al. 2017).

Different types of forest around the world have different amounts of carbon pool (CP) and rates of C sequestration. Oceania had the lowest CP as compared to other continents with only 16 gigatonnes of C, while South America had the highest CP of 103 gigatonnes of C. Asia and North Central America had quite similar CP of about 36 gigatonnes of C. Africa had CP of 60 gigatonnes, while Europe had only 45 gigatonnes of C. The rate of C sequestration also varies in different continents with the highest in South America and lowest in Europe (FAO 2016). Different types of medicinal tree of Sikkim, India, have different rates of C sequestration potential (Aggarwal and Chauhan 2014). Aboveground biomass had the highest CS as compared to the belowground biomass and LHG in Amhara, Ethiopia (Abere et al. 2017).

There is variation in C storage capacity according to the type of species, aspects, and vegetative parts. Species of *Pyrus ussuriensis* (Ussurian pear) has the highest annual C absorption rate as compared to *Pinus koraiensis* (Korean pine) and *Prunus davidiana* (Chinese wild peach) (Chen 2006). Sugi (*Cryptomeria japonica*) and hinoki (*Chamaecyparis obtusa*) forests of the southwestern region of Japan had higher C in biomass as compared to other parts of the country (Fukuda et al. 2003). Different species of *Pinus* had different C in their biomass in Spain (Gil et al. 2011). C stock also differs in different aspects of Himalaya (NE>NW>SE>SW) (Sharma et al. 2011). SOC was greater than biomass C in hills of Tamil Nadu (Ramachandran et al. 2007).

3 Forest as a Carbon Sink: Nepalese Context

There are different types of forest in Nepal according to different management strategies followed by the users. In the case of community forest (CF) of Nepal, local people manage the forest resource with the technical support of state forest agency, use it for their survival, and preserve it for future usage (K C et al. 2015). Till the date, there are more than 22,260 CF user groups in Nepal (DoF 2018). Establishment of these CFs in the hills had not only increased forest cover and C but also reduced the loss of C and other nutrients from the soil (Banskota et al. 2007; K C 2017). In the special focus to Nepal, its CF management had been taken as one of the successful examples of green economy and C sequestration throughout the world (K C 2016; Sukhdev et al. 2010).

C dynamics can be affected by biological, climatic, and other socioeconomic activities which always open the chances of future researches in it (Upadhyay et al. 2005). Management activities, utilization rate, and type of species present in an ecosystem can affect CS in forest ecosystem (Kalies et al. 2016). These forests have high capacity to absorb CO_2 of atmosphere and reduce emissions from deforestation (Shrestha et al. 2013; Thapa-Magar and Shrestha 2015). Also, active participation of local people by addressing socioeconomic problems had supported forest conservation and increased the forest biodiversity and CS (K C et al. 2015).

The greater the number of newly grown trees, the higher will be the amount of forest CS. It is further affected by type of species, age of the forest, quality of soil, local environment, and climate (K C et al. 2014; Shrestha et al. 2013). Also, type of forest, tree size, and management activities affect the CS and C sequestration potential of forest (Thapa-Magar and Shrestha 2015). In some *Pinus*-dominated forest, biomass C is higher than other mixed species as these species grow at a faster rate and are not taken by herbivores as their food (Aryal et al. 2013). In spite of providing essential forest products and other socioeconomic benefits to its user, it is helping toward reducing deforestation and natural disasters, increasing greenery and biological diversity, and absorbing CO_2 from the atmosphere in its vegetative parts (K C et al. 2014, 2015).

There may be different management strategies in force, but their ultimate aim is to use the resource sustainably and conserve it for the use of future generations. To increase the CS of the forest, new and renewable source of energy should be promoted in such area where C sequestration rate is less. It will help to increase the nonmonetary and monetary benefits from increased rate of forest C in the long run (Pandey et al. 2014a, b; Dhakal et al. 2015).

4 Methodologies for Assessing Carbon Sink

Researchers have applied different methodologies for assessing the forest C in global scenario and Nepalese perspectives. Some of them have used remote sensing technique for data collection, while many of them have measured CS directly in the field. In the process of field data conversion, they have used different allometric equations, biomass C models and conversion ratios, tree-specific densities, laboratory techniques of C measurement, and other techniques for CS measurement. They have also measured CS in different time intervals to observe the rate of C sequestration. In most of the forest C-related researches in Nepal, pilot inventory is conducted in the beginning for CS measurement along with focus group discussion with committee members (K C et al. 2014). Researchers usually follow the guideline prepared by the Ministry of Forest and Soil Conservation of Nepal for field measurement and calculation of CS (K C et al. 2013a, b, 2014). First of all, different methodologies applied by researchers in different locations of the world will be reviewed in this part, and a standard one which is followed in Nepal by researchers, and guided by a governmental research agency, will be discussed in brief.

4.1 Methods Applied by Researchers in Global Context

To assess the difference in CS of managed and unmanaged forests along with assessment of the costs and benefits of different forest practices, Kalies et al. (2016) conducted a meta-analysis through reviewing and extracting the secondary data from 35 literatures obtained from the United States, Canada, Korea, China, Spain, the Czech Republic, and Patagonia.

Abere et al. (2017) conducted a study to assess the C absorption capacity of Banja forest, at Amhara National Regional State in Ethiopia, by applying systematic sampling method in an interval of 888 m. Sixty-three samples of $20 \times 20\ m^2$ (square meter) were taken to measure height and diameter at breast height (DBH) of the trees, and further 5 subplots were sampled inside each plot to take sample of leaf litter, herbs, and grass (LHG) and soil.

Aggarwal and Chauhan (2014) had done a research to observe the economic and C absorption capacity of medicinal herbs in forest of Sikkim of India. The information about plantation activities such as area, time, and number of saplings was taken from the Forest Department. Also, plantation data from different ages and spaces was collected for analyzing the CS potential above the ground and under the ground. To know the distribution status and plantation strategy of species in different zones, secondary data of identified species was collected from the Department of Forest from Sikkim and National Medicinal Plants Board of Delhi. Firstly, biomass was calculated using height, cover, age, and slope. Secondly, cost-benefit analysis of different species was done from cost of plantation, maintenance, and fencing and benefit of forest products (fruits, seeds, leaves, timber, and firewood). Twenty samples of $25 \times 20\ m^2$ size (making a total area of 1 ha) were given consideration through field investigations during November 2009. To calculate the crown density, five species of trees were selected. For measuring biomass, height and DBH (1.37 m) were taken in the field. Equation suitable for a particular site was used to measure volume, while biomass was measured by taking volume and specific wood gravity. Fresh litter was collected from $1\ m \times 1\ m$ quadrat and later converted into ton per hectare.

With an objective to assess the traits of C storage in forest, Chen (2006) conducted a study in Northeast China in mixed broad-leaved Korean *Pinus* forest which lies at an altitude of 700–1600 m. Inside the sample size of area $50 \times 50\ m^2$, more than 500 trees were observed implementing tree ring analysis and allometric equations. Change in CS with increasing tree size was assessed by measuring diameter and CS.

Fukuda et al. (2003) conducted a study in sugi and hinoki forest to assess the C stored in forest of Japan by using standard raw data from national forestry censuses. CS of forests was calculated by using wood volume per hectare data available in regional level, biomass measurement models, and age structure of these forest types.

To assess the aboveground biomass C of M. Pizzalto forest inside Majella National Park in Italy, Bayat et al. (2012) used field data and modeled vegetation index data. For field observation of aboveground trees of Beech (*Fagus* spp.) forest, 50 sample plots were used to measure diameter and height. For using modeling, biological and other parameters such as slope, solar radiation, altitude, growing season time, type of soil, and management strategy were used. ArcGIS 9.3 was used to prepare geo-data along with boundary of the forest, rasterized vector maps, and 30 m pixels raster maps.

To assess the CO_2 absorption potential from aboveground biomass, Gil et al. (2011) conducted a study in Castilla y Leon forests of Spain with the help of species-wise data from forestry statistics. They have measured the aboveground biomass with the help of allometric models and biomass expansion multiplier from local area. CO_2 stored in biomass was measured by using biomass-carbon ratio and yearly sequestration rate of CO_2. To estimate the aboveground biomass, Spanish forest inventory data were used which covers 9,422,543 ha area across its nine different provinces. Specially, the data was taken from 2nd and 3rd forest inventories between 1996 and 2006 of Spain.

Sharma et al. (2011) conducted a study in seven different forest types of temperate area of Garhwal Himalaya in the northern region of India to compare the difference on tree C and SOC from difference in slope aspects. The old growing forest was studied in northeast, northwest, southeast, and southwest aspects (which makes altogether 28 stands). In each stand, 10 square quadrats of 0.1 hectare were taken (which equals a total of 280 samples) with a total area of 28 ha. Inside the plot, diameter and height of the trees were measured for tree biomass C along with SOC and other biomass C-related parameters. Slope angle was also measured with the help of clinometer to adjust the area of plot during field data calculation and further analysis.

Ramachandran et al. (2007) did a research on C storage in natural forest in Tamil Nadu. For this study, geospatial data (remote sensing and digital data) of 28 February 2002 was used from global positioning system (GPS), topographic maps, Erdas image 8.6, ArcGIS 8.3, and MSTAT software. Twenty-five sample plots of 20 m × 20 m were taken in each forest type to measure girth at breast height. Bivariate regression model was prepared by taking data of volume, girth at breast height, and height. Volume and specific gravity of wood for different species prepared by the Forest Research Institute were used to calculate the biomass of stem. SOC was estimated by Walkley and Black wet oxidation technique from the sample of soil taken from systematic random sampling method.

Ullah and Al-Amin (2012) conducted a study in Tankawati forest of Chittagong region of Bangladesh to assess aboveground and belowground C storage in naturally grown forest. The research was conducted with the help of field measurement, observation, and laboratory activities between January and December 2009. GPS was used to locate the point in the field by using systematic sampling technique. Altogether, 20 points of intersection were used for naturally grown forest, and 4-square sample plot of 400 m^2 was used for measuring C stored in trees in each point (80 plots). To measure shrubs, herbs, grass, and leaf litter, a square plot of 4m^2 was used in each point (20 plots). For trees, 774 numbers of 56 species were observed, and diameter and height were measured.

4.2 Methods Applied by Researchers in the Context of Nepal

Shrestha et al. (2013) performed a research in Dolakha district to observe the situation of CF in terms of CS. Allometric equations as well as tree ring analysis was carried out for aboveground biomass C estimation in 66 rectangular plots of 6 different forests. Inside the sampling plot of 25 × 10 m^2 size, diameter and height of the trees were measured for assessing biomass and CS. Tree ring analysis was helpful to estimate the biomass C of 2006 by subtracting the increase in size of ring through biomass analysis. The overall data was analyzed by regression analysis, ANOVA, and t-test in Microsoft Office Excel, statistical package for social survey (SPSS), and R software.

The difference in C sequestered by different aged CF in Nepal was assessed by Thapa-Magar and Shrestha (2015) in nine different community-managed Sal (*Shorea robusta*) forests of Dhading. Random sampling was used to select these 9 CFs out of 190 CFs of the district. Stratified random sampling technique was followed for taking sample plots covering 0.6% of the total area. Slope, aspect, canopy cover, and ground litter of forest were measured along with the diameter and height of the trees for biomass measurement. From three forests, biomass, CS, and SOC were measured and compared using ANOVA, correlation, and regression analysis.

Shrestha and Singh (2008) conducted a study in hilly region of Nepal having medium to steep slopes lying at an elevation of 400–1100 masl to assess the CS of plants and soil. In lower altitude below 500 m, forest is dominated by Sal and other low-lying species, while in the elevation of greater than 500 m, there is mixed pine and *Schima-Castanopsis* forest. Different samples of soil up to the depth of 70 m were taken with the help of core ring sampler from different land use and sent for laboratory analysis. Also, fine root samples were taken for analyzing nutrient content. For height and diameter measurement of trees and shrubs, three sample plots of 10 × 10 m^2 were used.

Pandey et al. (2014a, b) conducted the study in 105 CF of Chitwan, Gorkha, and Dolakha district of Nepal to assess the variation of CS in CF. The site has five major vegetation types which are lying in different location and social context. The change in CS from 2010 to 2013 was determined from 490 sample plots by stratifying them into dense and sparse forest using GIS. For CS of trees, diameter and height were measured from the plot with radius of 8.92 m, while in the case of LHG, destructive method was used in the subplot of radius 0.56 m. Diameter of sapling was measured in the subplots of radius 5.64 m inside the main plot for aboveground sapling C. The allometric models help to calculate the trees and sapling biomass, but dry to fresh weight ratio was used to measure the C in LHG.

The living biomass and its C in naturally grown and CF of Nepal were assessed by Bhatta (2004) in broad-leaved forest of Lalitpur district in central Nepal. Assessment of tree C and height and DBH of each tree was measured, while soil sample was taken for laboratory analysis for measuring SOC. Primary data gathered in the forest was analyzed by using various statistical techniques in Microsoft Office and SPSS.

To assess the biomass and CS of the forest, Dahal (2007) completed a research in a CF of Kathmandu valley. The biomass C and SOC of *Pinus* and mixed broad-leaved forest was measured by using allometric equations and soil C measurement methods in Sunaulo Ghyampe Danda CF of Kathmandu.

Karky (2008) had measured the C stored in shoot and root biomass, SOC, and the sequestration rate of C in three different community-managed forests of Nepal. He had done forest assessment by mapping the boundary, conducting preliminary survey, identifying sample size, delineating the sample plots, and measuring the primary data related to CS estimation of root biomass, shoot biomass, and SOC.

In order to assess the CS in community-managed forest of Bhaktapur district in Nepal, Aryal (2010) performed a research in Toudol Chhap CF of Sipadol with the help of primary and secondary data collection methods. Further, the CP of *Pinus* forest and mixed broad-leaved forest was calculated by using the simple forest inventory methods applied by different researchers of Nepal.

To compare the CP of three different types of forest in Nepal, Dhakal (2010) conducted a study in naturally grown forest, planted type of forest, and enriched forest of Pashupati CF of Sarlahi district in south central Nepal. For this case, CS measurement guideline prepared by the Ministry of Forest and Soil Conservation of Nepal was used for all types of CP of the forest.

In a project to facilitate governance and payment mechanism under Reducing Emissions from Deforestation and Forest Degradation (REDD) scheme in Nepal, ICIMOD (International Centre for Integrated Mountain Development), ANSAB (Asia Network for Sustainable Agriculture and Bioresources), and FECOFUN (2010) had conducted a research in 104 CFs of 3 watersheds of Chitwan, Dolakha, and Gorkha district of Nepal. Biomass C of shoot and root of trees, sapling, and LHG and SOC was measured in all sampling sites. For trees, DBH and height of each trees were measured in the field, while in the case of sapling, diameter was only measured. LHG was measured by destructive process, and SOC was determined by bringing sample for laboratory analysis.

Fig. 1 Researchers delineating boundary

Fig. 2 Researchers delineating boundary of the plot

Fig. 3 Researcher measuring diameter of the tree

To assess the CS status of forest resources utilized and management strategy of CF, K C et al. (2018) conducted a study between 2010 and 2015 in two different forests of Syangja district and Lalitpur district of Nepal. Both the sampled forests were lying at an altitude between 900 and 2000 masl but in different regions of

Fig. 4 Researcher measuring angle of the tree

Nepal. Altogether, 60 quadrats were studied in 2 forests for C estimation in shoot and root biomass and SOC. For Syangja district, primary data was measured in 2011 and 2014, while in the case of Lalitpur district, field measurement was done in 2012 and 2014. To assess the CS in all forms, guideline prepared by the Ministry of Forest and Soil Conservation of Nepal was used which consists collection of primary and secondary data and analysis of collected data by using different allometric and mathematical equations.

With an objective to assess the C in living biomass and SOC, Khanal et al. (2010) performed a research in two separate CF of Palpa district of western Nepal. Both the Lipindevi Thulopakho and Jarneldhara CF were dominated by *Katus* and *Chilaune* species of hilly area of Nepal. For both the forests, biomass of trees, poles, and sapling were assessed by measuring diameter and height in field and by using allometric models.

Khanal (2007) performed a research in Champadevi CF of Kathmandu which covers an area of 136.2 hectare. CS was measured in the field by assessing the height and diameter of each tree, and this raw data was further analyzed by using allometric equation to calculate the total CS.

To assess the CS of forest in watershed level, Bhusal (2010) completed his research in Nagmati watershed area inside Shivapuri Nagarjun National Park as a partial fulfillment of Master's degree course of Environmental Science in Tribhuvan University of Nepal. Biomass C as well as SOC was measured in the forest by following methodology of forestry analysis from the Ministry of Forest and Soil Conservation of Nepal. The biomass-related data was measured in the field from an area of 14 hectares, while soil-related data was collected from field observation and laboratory analysis.

Fig. 5 Researcher taking soil sample

Fig. 6 Researcher measuring LHG in the field

K C et al. (2013a, b) performed a research in one of the CFs of western Nepal (dominated by *Schima-Castanopsis* forest) to assess the climate change mitigation potential of CF of Nepal. Altogether, 40 sample plots of 250 m^2 circular area were taken corresponding to a total sampled area of 1 hectare for aboveground tree C measurement. Circular subplot of 100 m^2 area inside the main plot was taken for aboveground sapling C, while area of 1 m^2 was used for LHG C. The soil samples from the entire plot along with LHG sample were brought to the laboratory for further analysis. In case of trees, height and DBH were measured in the field, while diameter was measured only in the case of sapling. Allometric and other mathematical equations were used for assessing biomass, total C, rate of C absorption, and CO_2 reduction capacity of the forest (Figs. 7 and 8).

The CP in *Pinus* forest and mixed forest were assessed by Aryal et al. (2013) in Gwalinidaha CF of central region of Nepal. During the field study, 0.5% of sample

Fig. 7 Researcher taking notes in the field

Fig. 8 Instruments used in the field

was selected randomly in two different strata of the forest for determining the CS of the forest. Four plots of $10 \times 10\ m^2$ were taken in both the strata of the forest for measuring diameter and height of the trees. Also, sample plot of $1\ m^2$ was taken inside each larger plot for measuring the LHG C. Overall, C stored in trees, roots, LHG, and soil was assessed during the study.

4.3 Common Methodology Applied in Nepal for Assessing Forest Carbon

Researchers have used different methodologies for assessing forest C in Nepal. In the recent days, many researchers are following national forest C guidelines prepared by the Ministry of Forest and Soil Conservation (MoFSC 2011) along with other guidelines. Some researchers are still following previous methods for assessing growing stock of CF in Nepal prepared by forest department of the same ministry. In 2010, ICIMOD, ANSAB, and FECOFUN have prepared a CS measurement guideline as part of their project to facilitate governance and payment mechanism under REDD in Nepal with the funding of the Norwegian Agency for Development Cooperation (Subedi et al. 2010; Verma et al. 2015). This methodology was also followed by many researchers of these preparing institutions and even by other external researchers of Nepal.

Also, the World Wide Fund for Nature Nepal and Winrock International have prepared their own methodologies for assessing forest C in their different forestry-related projects in Nepal. These guidelines are prepared according to the climate, forest type, and other biotic and abiotic factors of forest in Nepal, but they are guided by international guidelines prepared by the Intergovernmental Panel on Climate Change (IPCC 2006), MacDicken (1997), Chave et al. (2005), and many more researchers and organizations. One of the most popular methodologies followed by researchers in Nepal is described in brief in this section.

In the beginning, researchers select their study area and conduct a preliminary field visit or a pilot inventory to observe the feasibility of a selected site and determine the size and number of samples. The preliminary survey is very helpful to include local forest users in CS measurement and other socioeconomic studies related to it. With the information of initial visit and other statistical techniques, researchers identify their sample size and number for their main study. Total area and boundary of the forest taken from the preliminary field visit also help to take random samples in the forest. GPS, topographic maps, satellite imagery, geographic information system (GIS), Google Earth images, local forest maps, and other remote sensing data prepared by forestry officials are also used for boundary delineation and sampling point identification.

Most of the researchers assess shoot biomass (tree, sapling, and LHG), root biomass, and SOC for assessing total C stored in the forest. For shoot biomass, plants having DBH less than 1 cm are taken as LHG, 1–5 cm are taken as sapling, and more than 5 cm are taken as trees. Representative samples of leaf litter, herbs, and grass and soil are gathered from forest and taken for chemical and physical analysis. Overall C stored in forest is calculated by adding all the types of C in shoot and root biomass and SOC. For calculation of rate of C sequestration, CS is measured in different time intervals in the same permanent plot which is used for measuring CS in the beginning.

4.3.1 Carbon in Shoot and Root Biomass

For C in the shoot of tree, researchers take sample plots of 250 m^2 (circular or square) or 100 m^2 (square) according to the feasibility of the area. The DBH (at 1.3 m) is measured with the help of standard diameter tape, and the height of individual trees is determined trigonometrically by measuring the angle of top and bottom with the help of clinometers or other similar devices inside each plot. In the case of height measurement, most of the researchers measure angle of the apex of tree and distance from point of angle measurement and use trigonometric equation to determine the height of the individual trees. They also use different baselines for taking sample of tree in the boundary of the plot (more than 50% basal area in the plot) and in the case of trees whose roots are the same but shoot is different. The collected data of diameter and height along with wood specific gravity of individual trees is used to calculate biomass of the tree by using Chave et al. (2005) allometric equations according to the climate and forest types. Further, IPCC (2006) default C fraction of 0.47 is used to convert biomass into C. This conversion factor is similar in the case of sapling, LHG, and belowground biomass for converting biomass into CS.

For aboveground sapling C, one subplot of 100 m^2 area (circular or square) is taken inside each larger plot, and diameter of the entire sapling is measured. The allometric biomass equation and table of Nepal prepared by forest ministry are used for taking slope and intercept of allometric relationship for saplings to calculate shoot biomass in sapling and further its C.

In order to measure the C stored in LHG, one or more subplots of 1 square meter inside larger plot (circular or square) are taken, and all the leaf litter, herbs, and grass are taken out by destructive method. Fresh weight of all the LHG is measured in the field, and composite sample is brought to laboratory for taking dry weight. The ratio of dry weight and fresh weight is used to calculate biomass of LHG and further its C. For all cases of C measurement in belowground biomass, aboveground and belowground ratio of 1:5 from MacDicken (1997) is followed by most of the researchers.

4.3.2 Soil Organic Carbon (SOC)

C present in soil is measured by assessing different parameters such as percentage of C, depth of soil, and bulk density of soil. Pearson et al. (2007) equation which uses all three parameters is used for calculating SOC as shown in Fig. 9. First of all,

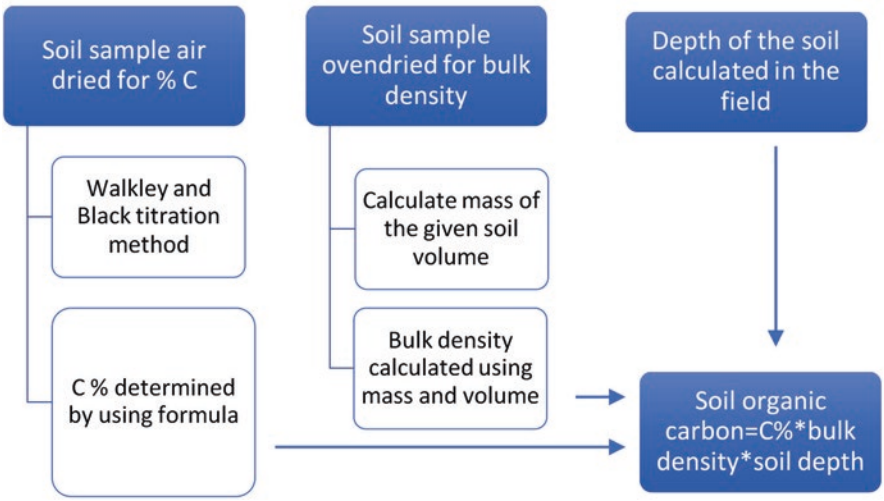

Fig. 9 Flowchart for SOC determination

one or more sample of soil is taken from each larger plot used for biomass C measurement. Sample of soil is collected by making a small pit of 30 cm as followed from IPCC (2006) default depth. In some cases, percentage of C is determined from each different depth up to 10 cm, between 10 and 20 cm, and from 20 to 30 cm, while in other studies, composite sample from the depth of 0–30 cm is taken for laboratory analysis. For bulk density of soil, standard metallic soil sampling corer of different volumes is used to take soil sample for oven drying. The sample for bulk density and percentage C is taken differently in the laboratory for further analysis. The amount of C present in soil is assessed in the laboratory by following Walkley and Black (1934) method.

5 Carbon Stored by Forest

In this part, the observation on CS of different researches across the world and Nepal is reviewed and documented below. It shows the potential of forests in C sequestration in different parts of the world.

5.1 Carbon Stored by Forest in Global Context

FAO (2016) monitors the forest around the world with respect to its status of management and utilization under the Global Forest Resource Assessment Project in 2015. It is done in regular interval to help in making decision for forest policy, investment, and sustainable development. From Table 1, it is observed that South America had the highest CS of 122 tons per hectare (ton/ha) with total CP of 103 gigatonnes in aboveground and belowground biomass, followed by Africa with a CS of 96 ton/ha with total CP of 60 gigatonnes. Overall average CS in the world is 73 ton/ha with total CP of 296 gigatonnes in aboveground and belowground biomass.

Kalies et al. (2016) observed that C contained in dry leaf, herbs, grass, and root had reduced in comparison to controls, but soil C and deadwood C were similar to that of treatment. All other types of CP had risen slightly after treatment, but the deadwood had declined with time. There was the highest loss of C in litter, roots,

Table 1 Carbon stock in the forest of the world in 2015 (Adopted: FAO 2016)

SN	Categories	Total carbon pool (GT)	Carbon stock (ton/ha)
1	Africa	60	96
2	Asia	36	61
3	Europe	45	45
4	North and Central America	36	58
5	Oceania	16	92
6	South America	103	122
	Total (world)	296	73

and vegetation because these parts are affected by management issues, while the soil was not affected by this issue. But as the time passes, the loss of C was higher as compared to earlier ones.

Aggarwal and Chauhan (2014) calculated that bahera (*Terminalia bellirica*) plantation had the highest per hectare C sequestration potential of 132 tons, while harar (*Terminalia chebula*) had potential of 71 tons, and amla (*Phyllanthus emblica*) plantations had per hectare C sequestration potential of 30 tons only. The yearly C sequestration rate per hectare for bahera plantation was 2.64 tons, harar was 1.42 tons, and amla was 1 ton. Internal rate of return of C from bahera was higher as compared to that of harar and amla.

Abere et al. (2017) reported that average aboveground biomass was 720.69 ± 503 tons per hectare, while average aboveground CS was 338.72 ± 236.41 tons per hectare in the forest with a range of 12.61–1187.04 tons per hectare and belowground CS was 67.74 ± 47.28 tons per hectare in the forest with a range of 2.52–237.41 tons per hectare. There was variation in biomass CS according to the type of tree species as *Juniperus procera* (African juniper) was absorbing 28.09% C with an average of 95.13 tons per hectare and *Ekebergia capensis* (Cape ash) was absorbing 19.42% C with an average of 65.79 tons per hectare. Similarly, average LHG biomass was near to 7.5 tons per hectare, while CS was near to 3.5 tons per hectare ranging from 0.98 to 4.21 tons per hectare. The average SOC was 230.82 ± 68.88 tons per hectare ranging from 88.47 to 358.07 tons per hectare. There was the highest soil C in middle altitude, the second in higher altitude, and the lowest in low altitudinal region. Overall, there was 230.82 ± 68.88 tons per hectare of C and 2348.32 ± 1077.84 tons per hectare of CO_2 which could generate C credit of around US $ 10, 000.

Chen (2006) revealed that Korean pine has the highest CS during its lifetime of 5683 kg, and Chinese wild peach has the least with 433 kg, while Ussurian pear has the highest annual C sequestration rate of 78 kg. Stem, root, and branch hold different C percentage, but on an average, stem holds greater than 68%; root, 20%; and leaf and branch, 10% of total CS of a tree species. Different tree species were holding different quantities of C as coniferous trees were holding more C than the deciduous trees. In the first 50 years, tree species which grow faster stores more C than the species which grow at a slower rate.

Fukuda et al. (2003) reported that biomass C was varying according to the type of forest in Japan. Biomass in branch of Hinoki forest was 5–10% higher than similar sugi forest, while biomass in the stem of Hinoki forest was 5–10% less than similar sugi forest. Sugi stores 346.4×10^6 Mg (megagram) of biomass C with a mean of 76.8 Mg C/ha, while hinoki forest stores 139.2×10^6 Mg of C with a mean of 58.01 Mg C/ha. Also, sugi and hinoki forests in the southwestern region of Japan have higher amounts of biomass C as compared to other parts of the country.

Bayat et al. (2012) mentioned that the total aboveground biomass in all 50 plots of old and newly grown beech forest in Italy was 618 tons, and the CS in biomass was 309 tons. Living biomass and stored C were 247 and 123 tons per hectare, respectively. It was also observed that different management strategies have different quantities of shoot C in that context.

Gil et al. (2011) stated that biomass absorbed by forests of Castilla y Leon region of Spain was 77,051,308 Mg at an average incremental rate of 8.18 Mg per hectare in 1996 and 135,531,737 Mg of biomass with an average incremental rate of 14.4 Mg per hectare in 2006. The total increase in forest C from 1996 to 2006 was 9,608,824 Mg per year. The provinces with higher biomass in the year 1996 were Burgos, Soria, Salamanca, and Leon holding 66% of biomass in the region as similar measurement in 2006. From mathematical equations, *Pinus pinaster* (Maritime pine) had greater biomass in 1996 and 2006, followed by *Pinus sylvestris* (Scots pine), *Quercus ilex* (Holm oak), *Quercus pyrenaica* (Pyrenean oak), and *Fagus sylvatica* (European beech). These species were holding 69% of living biomass of the area in 2006, while 2 other species, Maritime pine and Scots pine, represent 35% biomass in 2006, and two broad-leaved species, Holm oak and Pyrenean oak, absorb 27% of the total biomass in 2006. In between these 10 years, Holm oak, Pyrenean oak, Scots pine, and Maritime pine had the highest biomass absorption rate.

Sharma et al. (2011) witnessed that C storage was greatest in NE aspects, second on NW, and then SE and the lowest in SW aspect of the Himalaya. Northern part has stable living communities with high fertile soil content and higher amount of CS. The average tree C in the planted forest in temperate area was 64 Mg per hectare. Aboveground biomass density ranges from 134.1 ± 10.6 megagrams per hectare on southwest aspect of *Pinus* forest to 518.2 ± 44.8 megagrams/ha on northeast aspect of *Cedrus* forest. Similarly, belowground biomass density varies from 35.0 ± 2.5 megagrams per hectare on southwest aspect of *Pinus* forest to 115.6 ± 10.5 megagrams per hectare on northeast aspect of *Cedrus* forest. Likewise, biomass ranges from 169.2 ± 13.1 megagrams per hectare on southwest aspect of *Pinus* forest to 633.8 ± 55.3 megagrams per hectare on northeast aspect of *Cedrus* forest. But the total tree C density varies from 77.3 ± 10.7 C Mg per hectare in *Quercus* forest to 291.6 ± 25.4 C Mg per hectare in *Cedrus* forest. The SOC varies from 40.3 ± 5.5 C Mg per hectare on southwest aspect of pine forest to 177.5 ± 15.4 C Mg per hectare in *Cedrus* forest.

Ramachandran et al. (2007) found that the C in biomass of hills of Tamil Nadu was 2.74 teragrams and SOC was 3.48 teragrams. As the SOC was higher than biomass C, their ratio was 1.18. The amount of root and shoot C stored in biomass was 2.74 teragrams among which semievergreen forest holds 22%, deciduous type consists of 57%, and other forests consist of 21%. Similarly, C in the biomass of semievergreen, deciduous, secondary deciduous, thorn, and *Euphorbia* forest was 0.60, 1.57, 0.35, 0.22, and 0.01 teragrams per hectare, respectively. The calculated data was similar to that of tropical forest whose C density in biomass varies from 63.33 to 156 tons per hectare. SOC in the surface of Kolli hill soil ranges from 0.1% to 9.7%, middle layer from 0.1% to 5.38%, and bottom layer from 0.1% to 4.92%.

Ullah and Al-Amin (2012) observed that *Dipterocarpus turbinatus* (gurjan) species has the greatest total biomass of 81.42 tons per hectare and total C storage of 45.40 tons per hectare, while *Antidesma acidum* (Archal) species has the least total biomass of 0.06 ton per hectare and total C of 0.04 ton per hectare. *Melastoma malabathricum* (Indian rhododendron) species has the greatest total biomass of 134.42 kg per hectare and total C of 69.47 kg per hectare, while *Leea* species has the least total biomass of 12.07 kg per hectare and total C of 5.11 kg per hectare out of 12 shrub species. In the case of 14 herbs and grass species, *Cynodon dactylon* (doob grass) has the greatest total biomass of 34, 911 kg per hectare and total C of 76.05 kg per hectare, while *Derris trifoliata* (Karanjvel) has the least total biomass of 17.82 kg per hectare and total C of 1.50 kg per hectare. SOC was the highest at the depth up to 1 cm with 0.13 ± 0.01 ton per hectare per centimeter. Overall, CS in trees was 38%, undergrowth with 3%, and soil and litter with 59% of total C storage of the forest.

5.2 Carbon Stored by Forest in the Context of Nepal

With the support of the Government of Finland, the Government of Nepal had implemented Forest Resource Assessment in Nepal project under the Department of Forest Research and Survey, Ministry of Forests and Soil Conservation. This project assessed resources of the forest in the country level in all the physiographic zones. It was observed that total CS in the forest was 176.95 tons/ha, mainly dominated by the tree component (108.88 tons/ha) (DFRS 2015) (Table 2).

Similarly, it was observed that high mountains and high Himal had the highest CS of 152.36 ton/ha in tree components and 114.03 ton/ha in soil. Secondly, Terai region had the CS of 104.47 ton/ha in its tree components and 33.66 ton/ha in the soil (DFRS 2015) (Table 3).

Pandey et al. (2014a, b) reported that the mean CS in dense strata was higher than the sparse strata of forest. There was variation in CS in different dominating species types with the highest in Sal forest, second in *Rhododendron-Quercus* forest, and least in *Pinus* forest mixed with *Schima-Castanopsis*. There was variation in CS from 0.6 megagrams C per hectare in less dense *Pinus* forest to 345.1 megagrams C per hectare in dense Sal forest. There is higher rate of increase in C flows in *Pinus*-dominated forest followed by *Katus-Chilaune* and mixed broad-leaved forest.

Table 2 Carbon stock in the forest of Nepal (DFRS 2015)

SN	Categories	Carbon stock (ton/ha)
1	Tree component	108.88
2	Litter and debris	1.18
3	Soil	66.88
	Total	176.95
	Total carbon pool in forest of Nepal	1054.97 million tons

Table 3 Carbon stock (ton/ha) of forest in different physiographic zones of Nepal (DFRS 2015)

SN	Categories	Terai	Churia	Middle mountains	High mountains and high Himal
1	Tree component	104.47	97.69	79.42	152.36
2	Litter and debris	0.28	0.32	1.65	1.47
3	SOC	33.66	31.44	54.33	114.03

Yearly C increment was 5 megagrams C/ha in Sal forest, 5.8 megagrams C/ha in mixed forest having broad leaves, and 6.2 megagrams C/ha in *Katus-Chilaune* forest.

Shrestha et al. (2013) found that the biomass of six different forests varies from 1400 to 13300 tons with an average biomass of 4000 tons at an increment of 70.8 tons/ha with annual increment of 1.53 ton/ha. Mixed type of forest stands had less biomass as compared to that of pine-dominated forests. In terms of yearly increment of C per hectare, CF absorbs 2 tons of C and proves that it is regulating global CO_2 emission.

Thapa-Magar and Shrestha (2015) measured the mean biomass as 254 Mg per hectare with a range of 149–389 Mg per hectare in the forest. Similarly, CS was ranging from 70 to 183 Mg C per hectare having a mean of 120 megagrams C/ha. Biomass and CS were higher but not significantly in the forest which was managed more than 10 years as compared to the one which was managed less than 10 years. It might be due to increase in diameter and height of trees with the increase in time duration. The annual rate of C sequestration was 2.60 Mg C per hectare or 9.54 Mg CO_2 per hectare showing that there is CO_2 mitigation in CF of Nepal.

Shrestha and Singh (2008) observed that total biomass C was ranging from 65 Mg per hectare to 228 Mg per hectare. In case of trees, aboveground C was 169 ± 26 Mg per hectare, and belowground C was 50 ± 8 Mg per hectare, while C in shrub was ranging from 8 Mg per hectare to 27 Mg per hectare. The C in trees was many times higher than that of shrubs and herbs in dense forest managed by community. The average SOC was ranging from 14 to 19 g per kg in surface layer near to the soil with the highest in unirrigated soil, followed by irrigated soil and *Schima-Castanopsis* forest. There was variation in biomass C in different plant types with the highest in *Shorea* forest, second in degraded forest, third in pine-mixed forest, and least in *Schima-Castanopsis* forest.

Naturally grown forest had higher aboveground C as compared to community-managed forest in Phulchowki region of Nepal. The aboveground C in community-managed forest was ranging from 55.30 to 67.04 tons per hectare, while in the case of naturally grown forest, it was ranging from 91.89 to 112.79 tons per hectare. Also, SOC was greater in naturally grown forest as compared to community-managed forest. The SOC in community-managed forest was ranging from 150 to 160 tons per hectare, while in the case of naturally grown forest, it was ranging from 195 to 223 tons per hectare (Bhatta 2004).

Khanal (2007) reported the biomass of *Quercus floribunda* (Moru oak) was the highest in Champadevi CF as compared to other species. There was comparatively low CS of 24.72 tons per hectare as compared to other community-managed forest and natural forest of the district and the country.

Dahal (2007) observed that CS of *Pinus* forest was 116 ± 16.39 tons per hectare, while in the case of mixed broad-leaved forest was a quiet low of 25.95 ± 8.09 tons per hectare. SOC in soil having *Pinus* forest was 10.12 ± 1.03 tons per hectare, while in the case of broad-leaved forest, it was in more amount equal to 24.62 ± 1.18 tons per hectare. The annual sequestration rate of C was higher in mixed broad-leaved forest (2.95 tons per hectare) as compared to *Pinus* forest stand

(1 ton per hectare). The annual monetary advantage of CF from C credit was US $ 563.15 in that forest.

Karky (2008) mentioned that CS in CF of three different forests of Nepal was 138 tons per hectare which is equivalent to 504 tons of CO_2 per hectare by excluding shrubs, leaf litter, herbs, and grass. The yearly C sequestration rate of biomass C in CF was ranging from 1.93 tons per hectare to 7.06 tons per hectare which shows potential in absorbing atmospheric CO_2.

Aryal (2010) revealed that there was higher CS in *Pinus* forest as compared to mixed type of broad-leaved forest near the capital city in central Nepal. Pinus forest had CS of 167.04 tons per hectare, while mixed broad-leaved forest had CS of 101.91 tons per hectare.

While comparing three different types of forest of the southern part of central Nepal, naturally grown forest had more C stored in it, while planted forest had medium CS, and enriched forest had the lowest out of the three. The total C absorbed by naturally grown forest was 181.83 ± 26.34 tons per hectare, planted type of forest was 159.49 ± 31.96 tons per hectare, and enriched forest was 133.65 ± 37.05 tons per hectare (Dhakal 2010).

By assessing the total CP, ICIMOD, ANSAB, and FECOFUN (2010) observed that Kayarkhola watershed of Chitwan district had the highest C storage of 296.44 tons per hectare in dense strata and 256.70 tons per hectare in sparse strata. Charnawati watershed of Dolakha district had medium C storage of 228.56 tons per hectare in dense strata and 166.75 tons per hectare in sparse strata, while Ludikhola watershed of Gorkha had the lowest C storage of 216.26 tons per hectare in dense strata and 162.98 tons per hectare in sparse strata. The highest difference of total C storage between two different strata was in Charnawati watershed, followed by Ludhikhola watershed and Kayarkhola watershed. One hundred and four different CFs had different storage of CS in their shoot, root, and soil.

In the case of Gwangkhola Sapaude Babiyabhir CF of Syangja, there was a rise in different forms of biomass C in the time duration of 2011 and 2014 which was similar to that of Kafle CF of Lalitpur in the duration of 2012 and 2014. Aboveground tree C was the highest in both cases, while sapling and LHG biomass were quite less similar to the result of other studies in Nepal. CP in GSBCF had increased from 122.29 tons per hectare in 2011 to 155.04 tons per hectare in 2014, while in the case of KCF, it was increased from 107.10 tons per hectare in 2012 to 110.13 tons per hectare in 2014. The yearly C absorption rate in GSBCF was 8.19 tons per hectare, while in the case of KCF, it was 1.52 tons per hectare (K C et al. 2018).

Khanal et al. (2010) narrated that biomass C in Jarneldhara forest was low due to the presence of newly grown trees as compared to that of Lipindevi Thulopakho forest, but it was reverse in the case of SOC and total CS. The biomass C was very low in LHG and sapling as compared to that of whole tree C, and the SOC was different with changing depth below the ground surface and contributing to about 68% of total CS. The C in shoot in Jarneldhara and Lipindevi Thulopakho CF was 36.6 ± 3.4 tons/ha and 40.2 ± 4 tons/ha, respectively. Similarly, soil C in Jarneldhara CF was 121.4 ± 7.4 tons per hectare, and Lipindevi Thulopakho CF was 94.6 ± 4.4 tons per hectare.

Total CS and SOC in sampled 14-hectare area of the forest was 9782.11 ± 25.18 tons. It was estimated that total CS of the Nagmati watershed was 167442.26 ± 42076.82 tons, while biomass CS of Shivapuri Nagarjun National Park was 699961.20 ± 175894.32 tons (Bhusal 2010).

K C et al. (2013a, b) reported that C stored in aboveground tree was the greatest with 59.36 tons per hectare, followed by SOC with 45.18 tons per hectare, LHG C with 3.54 tons per hectare, and sapling C of 1.35 tons per hectare. *Schima wallichii* (Chilauni) had the highest CS of 29.80 tons per hectare, followed by *Castanopsis indica* (Indian chestnut) with 27.10 tons per hectare, *Engelhardtia spicata* (Mauwa) with 6.40 tons per hectare, and other species with 9.56 tons per hectare. The yearly absorption rate of C in the forest was 0.45 ton C per hectare and 1.64 tons CO_2 per hectare.

Aryal et al. (2013) estimated that total C stored by the forest was 2250.24 tons, while the mean C stored per hectare was 166.68 tons per hectare. Also, there was higher tree C stored in *Pinus* forest as compared to that of mixed forest, but the case was reverse in the case of LHG. The average C stored in *Pinus* forest was 217.73 ± 71.05 tons per hectare, while in the case of mixed forest, it was only 115.29 ± 13.12 tons per hectare. The C in aboveground tree, root, and LHG of *Pinus* forest was 138.60 ± 54.87 tons per hectare, 34.65 ± 13.71 tons per hectare, and 0.29 ± 0.14 tons per hectare, respectively. But, the C absorbed by tree, root, and LHG in the case of mixed forest was 43.53 ± 10.03 tons per hectare, 10.88 ± 2.51 tons per hectare, and 0.36 ± 0.12 tons per hectare, respectively.

6 Forest Carbon Sink and Sustainability

Forest being one of the major sinks of global atmospheric CO_2 is challenged by its deforestation and degradation (Houghton and Nassikas 2018; Jhariya 2017; Yadav et al. 2017; Raj et al. 2018a, b). Increasing the rate of C sequestration and maintaining high CS in forest are quite challenging. Increase in population and their high needs of forest resources are increasing the rate of deforestation (FAO 2016). The natural and highly productive forest of tropical areas is deforested day by day which is decreasing its capacity of C sequestration (Houghton and Nassikas 2018). Other highly productive forests of Northern Hemisphere are being deforested for industrial and commercial use. This is bringing high risk for sustainability of forest C sequestration in global context. But it cannot be ignored that conservation of forest and increasing the CS is one of the cost-effective methods of reducing atmospheric CO_2 and minimizing global warming and climate change impacts (K C et al. 2013a, b; Jhariya and Raj 2014).

CS in Nepalese scenario is quite similar to the global context in low altitude region, but it is totally different in middle- and high-altitude region. The forest of Terai and lower altitudes where there is easy access of people and their transportation means is highly destroyed resulting in low CS and C sequestration rate (Chaudhary et al. 2015; Sihag et al. 2015). Most of these forests are deforested for constructing roads and other infrastructures of development. But the forest in higher altitudes managed by local community is getting denser resulting in increased CS and C sequestration rate (K C et al. 2018). The users of forest in higher altitudes are decreasing and are shifting from traditional energy sources (firewood) to modern ones such as liquefied petroleum gas, solar energy, hydroelectricity, and natural gas. Hence, the sustainability of CS and C sequestration is challenging in lower altitude of Nepal but can be achieved in higher altitudes.

7 Future Research and Development

From the previous sections, it is observed that researches in the global context are sufficient enough to find the CS and C sequestration rate. Field observations and remote sensing techniques are used to assess the C absorbed by forest and soil. It is necessary to continue these researches in long term for accurate determination of CS and C sequestration rate.

The researches in Nepal are still inadequate to assess the CS and C sequestration rate. The measurement from remote sensing techniques can be done easily, but the field verification is really challenging due to remoteness and lack of transportation means. Still, researchers are attempting to reach each and every part of the country for field observation and verification. Limited financial and technical resources are binding students and researchers to accurately assess the forest and soil C across the country. It is necessary to focus more toward researches on CS of forest in higher altitudes and remote areas.

8 Discussion

From the above reviews, it can be seen that researches are conducted in different types of forest in the world for determining C in the shoot and soil. Type of methods used for analysis of C is also different depending on the location and type of forest species. The method used for selection of sample site is quite similar in most of the researches as they are using different types of remote sensing techniques, topographic maps, and global positioning system. Also, statistical techniques are implemented for determining number and intensity of sample quadrats based on the pilot surveys. Use of these techniques for selecting random sample plots will decrease biases in data collection. For data collection, remote sensing imageries, field-based calculations, and secondary data from official sources are collected. The remote sensing data might be easier and reliable to collect, but it should be verified by field observation and measurement. Analysis of data is done by using statistical methods, allometric equations, reference table of wood specific density and slope factor, and mathematical equations. Different analytical software such as Microsoft Excel, SPSS, R, and ArcGIS are also used by researchers. Allometric equations and models combined with statistical techniques need to be updated in regular time interval for accurate assessment of CS.

In the global context, CS of the forest is affected by its management and usage pattern (Kalies et al. 2016). Different regions of Spain have variation of CS in their forest according to the type of species present in it (Gil et al. 2011). Forest of African region has different CS in biomass and soil according to the type of species and altitudinal ranges (Abere et al. 2017). Different forest types in India and Bangladesh of South Asia have different amount and proportion of CS according to the type of tree species and rate of harvest (Aggarwal and Chauhan 2014; Ramachandran et al. 2007; Sharma et al. 2011; Ullah and Al-Amin 2012; Buragohain et al. 2017). In the northeastern part of China, forests have different proportions of C in its stem, root, and branches (Chen 2006). There was variation of biomass C in branch and stem in hinoki and sugi forest in Japan, but these forests in the southwestern part have higher C in biomass as compared to other regions of the country (Fukuda et al. 2003).

In the Nepalese context, C in aboveground biomass had increased in most of the studies (Pandey et al. 2014a, b; Thapa-Magar and Shrestha 2015). The C in aboveground tree biomass was the highest in most of the cases (K C et al. 2013a, b), while few forests have the highest C in the soil (Bhatta 2004). Compared to the C in trees and soil, contribution of sapling and leaf litter herbs and grass is minimal (K C et al. 2018). In the *Pinus* forest type, C sequestration rate was more in mid-hill areas than other forest types in the nearest locality as this species is fast growing and unpalatable for the users (Shrestha et al. 2013). Evergreen and subtropical forest in the lower altitudes had higher total CS due to higher productivity as compared to that of coniferous and deciduous forest type of higher elevation (ICIMOD et al. 2010; Pandey et al. 2014a, b; Meena et al. 2018b). C sequestration rate is totally dependent upon the use of forest resource from the forest so it varies throughout the country. As compared to utilization rate, renewable rate of forest was higher which produces positive C sequestration rate in most of the forest. In some hilly part of Nepal, users of forest are decreasing due to migration and shifting to other energy technologies. This also leads to increase in greenery, floral biodiversity, and CS of the forest.

9 Conclusion

Overall, forest had potential of reducing atmospheric CO_2 as it is the storehouse of C. Management of forest is the important aspect of the forest to increase CS, so monetary and nonmonetary incentives to these managers will further help to enhance the rate of C absorption in the future. Reducing emission from deforestation and forest degradations and payment for ecosystem services will provide economic incentives for the managers to reduce the use of forest and increase the C storage in the forest.

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Properties and Importance of Various Bamboo Species for Multi-Utility Applications

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Abstract

Bamboo, with the potential to grow on wasteland, has emerged as the most appropriate alternative to wood. Low weight to height ratio, high growth rate, tensile strength comparable to materials like steel, and ability to grow on wasteland as well make it a most sought-after material. Bamboo fascinates people by its vivid color and fine particle structure. Easy availability, rapid growing speed, and ability to sustain in wastelands make it most desirable material for building and construction industry. The usage of bamboo varies from household products, handicrafts, and laminated panels to pulp and papermaking industries. Bamboo is available in 90 genera with about 1200 species. The major constituents of bamboo culms are cellulose, hemicelluloses, and lignin (about 90% of the total mass) with resins, tannins, and waxes as the minor amount. Trace amount of inorganic salt is also found in it. Mechanical properties and durability of these species depend on their chemical composition. This chapter presents the information regarding the economic and ecological importance of bamboo species. This chapter tries to assimilate the knowledge about the constituents of various bamboo species available across the globe. In addition to this, factors that affect the quality of bamboo culms in service life are also discussed. Biotic factors include the resistance of culms to various microorganisms and insects attacking the culms alone or in succession. Non-biotic factors like rain, moisture, and weathering are also described here. Knowledge about basic features and properties of these species is required to formulate the strategies for specific uses of these species making it a more valuable product. Livelihood opportunities in the field of bamboo products from Indian perspective are explored. Challenges to wider application of bamboo along with future potential are also discussed here.

Keywords

Bamboo · Constituents · Durability · Bamboo applications · Utilization potential · Rural development

Abbreviations

AC Ash content
C Carbon
CC Cellulose content
LC Lignin content

1 Introduction

Continuous increase in human population coupled with modern lifestyle has generated huge demand for wood and wood-based products in service sector causing severe deforestation. Hence, for achieving sustainable development, non-woody forest products have to be given due attention. Bamboo a unique creation of nature assumes great significance in this context with several environmental benefits. The hollow internal structure makes it lightweight and easy to work with and transport.

Bamboo is a grass belonging to Gramineae family, found in tropical, subtropical, and mild temperate zones (46° north – 47° south latitude). Bamboo exists in about 90 genera divided into about 1200 species (Lobovikov et al. 2005). High growth rate and easy availability make it superior in properties than wood species (Yang et al. 2008).

Most of the properties of bamboo depend on following factors:

- Bamboo species with different age are known to possess different physical as well as chemical properties. As bamboo culm ages, fiber length varies, thus affecting the overall characteristics of the culm (Li et al. 2007; Wang et al. 2016).
- Liese and Kumar (2003) reported that the harvesting time affects durability of bamboo. One week, once moon reaches full moon phase, is known to be related to low capillary water in the bamboo's culms. In addition to this, dry seasons are related to high starch content, and thus greater possibility of microbial attack is there. Rainy seasons are traditionally considered to be ideal time to harvest bamboo species (Kaur et al. 2016d).
- It has been reported in literature that the physicochemical properties grown on different climatic conditions are different. Thus it is essential to know the geographical location of species, where it is grown to know about its specific properties (Kaur et al. 2016c).
- Bamboo culms stored under moist conditions are under ideal conditions for fungi and insects to grow. Traditionally, storing in kitchen over fire place and submerging in running water are considered to be suitable for long-term storage of bamboo species (Liese and Kumar 2003).
- Strength properties of nodal and intermodal sections are reported to be different. The fact is strengthened by studies performed by Ahmad and Kamke (2003), which reported the significant variation of mechanical properties between these two sections. Similarly, Oka et al. (2014) found that the tensile strength parallel to grain varies between nodal and internodal sections. Deng et al. (2016) reported nodal sections are responsible for providing the strength to the culm.
- Strength is known to vary with the height of the culm. While the compressive strength shows a positive correlation with increase in height, the bending strength follows a negative pattern and decreases with height. Literature studies highlight the fact that properties depend on the part of the culm under consideration. It has been found that the shear, compressive, and tensile strength was higher at the top than at the bottom (Oka et al. 2014; Deng et al. 2016; Meena et al. 2016).

Compared to steel, concrete, and timber, less mass of bamboo is able to withstand more loads. The tensile strength of bamboo (28,000 lb./in^2) is much higher than steel (23,000 lb./in^2). It is reported that 50 times less energy is required to generate 1 m^3 per unit stress for bamboo as constructional materials as compared to steel or concrete. This makes bamboo a suitable alternative to steel in load-bearing applications (Rahman et al. 2011). It has been used for household utilities, handicrafts, chairs, etc. (Fig. 1).

Socio-environmental values associated with bamboo make it an alternative material for housing and handicraft, in addition to its wide use in pulp and paper industry. Hollow internal structure of bamboo culms makes it lightweight and easy to work with and transport. Bamboo being easy to split is used in woven industry.

Figure 2 shows the bamboo forests shared by different countries. Asia is the major bamboo-producing continent, with leading countries as India, China, and Indonesia (Lobovikov et al. 2005). In Asia particularly, with large-scale planting of bamboo, the forest area cover has been increased by 10%.

Asia being the biggest grower of bamboo species is the biggest exporter as well. Industrialized bamboo products contributed to 29% and bamboo woven products about 25% to the total share of bamboo export (Fig. 3).

Like wood, the major chemical constituents of bamboo are lignin and cellulose. Although extractives constitute minor proportion of the culm, they significantly affect the pulp making process and cost of bleaching. Bamboo is an extremely diverse plant with around 1200 literature reported the species (Ben-Zhi et al. 2005; Sihag et al. 2015).

Variation of chemical constituents of these species affects the utilization of bamboo resources. Only a few of these species are utilized for specific applications,

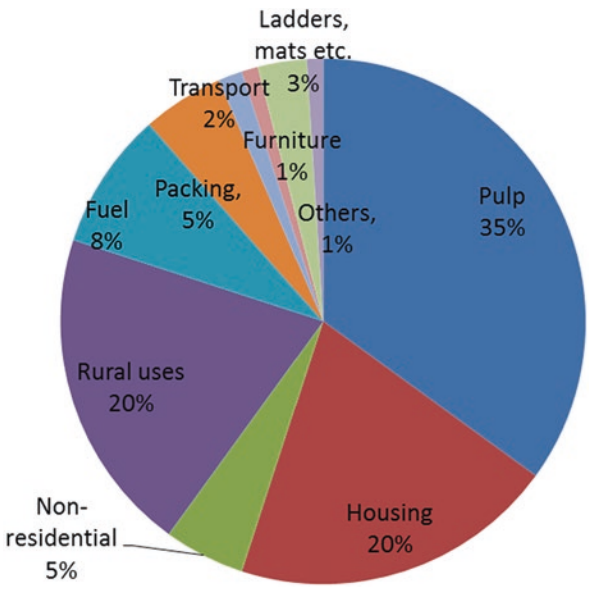

Fig. 1 Different uses of bamboo species. (Adopted: Kaur et al. 2016b)

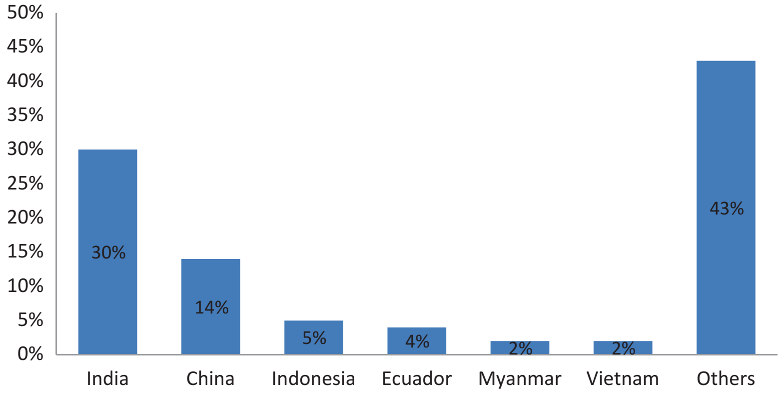

Fig. 2 Worldwide distribution of bamboo. (Adopted: Lobovikov et al. 2005)

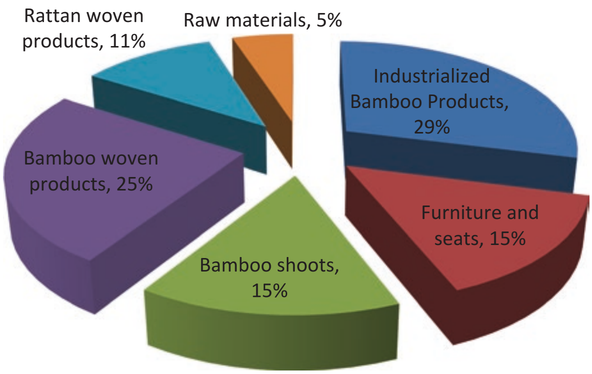

Fig. 3 World trade of bamboo and products. (Adopted: INBAR Report 2012)

while rests of the species are being neglected. Lack of knowledge about total extractive contents and lignocellulosic properties led to their restricted utilization potential. The poor life span of untreated bamboo species (less than 6 months) under field conditions is the greatest hindrance for their wider application (Kaur et al. 2016c, d). Though for timbers, various study documents on specific properties and field of utilization of various species are easy available, the systematic documentation of this information is lacking in literature.

One single parameter is not beneficial to consider a bamboo species for a particular application. For instance, selection of bamboo material requires high physical strength, durability, sustainability, and financial viability. In addition to this low content of water, extractives and starch constituents are desirable factors. Furthermore, pulp and paper industries require species with high CC, long service life with minimum hassles to remove lignin constituents. Species with high lignin content (LC) results in high pulping and bleaching costs. Though high CC is known to be beneficial for pulp making industry as it gives better pulp yield, LC and other extractives are required to be in low amount for the same application.

However, the wide variety of bamboo species give it a significant variation in properties, which affects the quality of finished product. For instance, brightness of pulp and mechanical strength of laminated bamboo boards varies with change in extractive contents. Therefore, the first step toward application of bamboo is the right choice of species for particular application. When it is utilized to produce biomass energy, the effect of various constituents on hydrolysis and fermentation process cannot be ignored. While the chemical constituent of bamboo varies from species to species, there is a significant variation of property in the same species as well. Thus, its evaluation of specific properties is of prime importance, and the effect of geographical location of growth should also be considered.

This chapter aims at the collection of information available in the literature. Ecological importance of bamboo is mentioned here. In review of physicochemical properties, durability of available bamboo species is used to make recommendations for selecting specific species for selected applications (Kaur et al. 2016d). Knowledge gaps in literature have been identified, and future scope for the value addition has been discussed.

2 Ecological Role of Bamboo

Bamboo is a plant, processing of which is simple and requires no special skill and equipment. This leads to low initial investment in bamboo-based industrial ventures. Thus it is a plant with high economic value especially as a furniture and building material. There are numerous ecological benefits as well associated with this plant. Its special properties make it ideal to solve many of the ecological problems facing by the world today such as deforestation, soil erosion, water shortage, landslides, etc. Broad shallow rhizome-root system and its accumulated leaf mulch make it a splendid material to conserve soil and retain moisture, reinforcement of embankments, drainage channels, etc. It is also found to be an excellent source as carbon (C) sink and effective in mitigation of greenhouse effect (Bhalla et al. 2008; Meena and Yadav 2015) (Fig. 4).

2.1 Reduces Deforestation

The high growth rate of bamboo makes it best alternative to wood. Bamboo is considered as fastest-growing, maximum-yielding plant. The high growth rate (30–100 cm daily during the season of growth), which can grow as tall as 36 m and diameter between 1 and 30 cm, makes it a highly renewable resource. The growth rate is so high that it can achieve its full height in a period of only 2 months with low weight and high strength properties (Ribeiro et al. 2017).

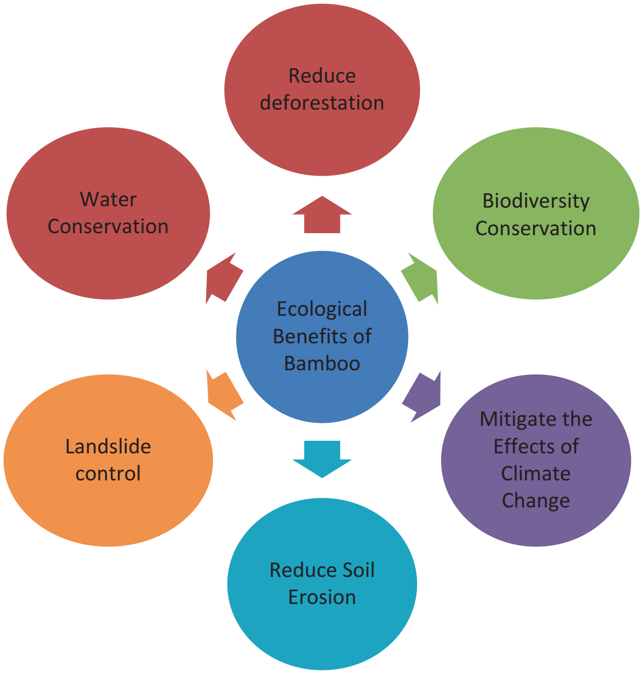

Fig. 4 Ecological benefits of bamboo. (Ben-Zhi et al. 2005)

2.2 Reduces Soil Erosion

Deforestation, overgrazing, tillage, and unsuitable agricultural practices in the past have substantially resulted in degradation in the quality of soil. In the present time, deforestation is a major threat faced by the terrestrial ecosystems, which can lead to loss of soil water holding capacity and thus result in water deficient dry lands (Panagos et al. 2014). It is estimated that the global annual soil erosion rate is 75 billion tonnes (Pg) from arable lands, causing annual loss of US$ 400 billion (FAO report 2017). Bamboo with less maintenance characteristics can grow well on wastelands and steep slopes. The credit of this unique feature of bamboo goes to its extensive fibrous root system and connected rhizome system. It also has leafy mulch and dense foliage, which produces new culms from underground rhizomes. This helps in the harvesting process with minimum disturbance to soil and thus helps in the reduction in soil erosion (Ben-Zhi et al. 2005; Dadhich et al. 2015).

The anti-erodibility of bamboo is reported to be much higher than wood species. For instance, Tardio et al. (2017) performed studies using bamboo plants on the riverbanks to control floods and soil erosion. The case study of Danav Khola River in Nepal involved riverbank protection using bamboo plantation along the shore, which were able to resist the drag of flood water.

2.3 Landslide Control

Landslide is not only a threat to topsoil loss but also dangerous for human and animal life. Bamboo is found to be highly effective in the control of landslide. Usually common bamboo is the most grown on places vulnerable to landslides. The results of studies performed in Japan are very encouraging in this aspect. It was found that *Bambusa multiplex* (hedge bamboo) is able to control erosion for more than 100 years (Shibata et al. 2002).

2.4 Water Conservation

The leafy litter of a plant is related to its ability to retain moisture and prevent soil erosion. The leafy mulch helps to improve the absorption and retention of moisture content more efficiently by reducing the rate of evaporation. Bamboo litter is reported to contain a high water retention capacity. As per literature review, the bamboo plant shed its leaves between the ages of 12 and 18 months to replace it with new leaves. It has been found that a single bamboo strand can hold 5 kg of water, which can strengthen 4 m^2 area of the soil. According to Hui et al. (2003), moso bamboo (*Phyllostachys edulis*) forest (1 ha area) can store up to 4200 tonnes of water before saturation. The relative humidity of bamboo forests is reported to be 5–10% higher than other woody fields during the summer (Xiao 2001).

The bamboo forest is reported to be associated with a higher capacity to conserve water. The studies performed by Wu et al. (1992) elaborated the effect of types of tree grown in a forest the total moisture capacity of forest soil. It was found that when the bamboo forest was mixed with broadleaf, the total moisture capacity of forest soil was very high. Further, it has been reported that pure bamboo forest has the highest non-capillary moisture capacity. It is believed that the high amount of culm stumps, dead rhizomes, and roots of bamboo forest after felling provides this non-capillary pore to absorb sufficient amount of moisture.

2.5 Mitigate the Effects of Climate Change

Bamboo as mentioned above is gifted with rapid growth rate and allows the collection of organic C (Lobovikov et al. 2012). As compared to other plant species, the areal distribution of bamboo is quite high, and it is estimated that it would sequester more C and thereby helps to decrease the severe effects of changing climate (Nath et al. 2015). Moso bamboo forest in China was reported to daily sequester 5.10 Mg ha^{-1} of C, which is 33% and 41% more than a tropical mountain rainforest and *Cunninghamia lanceolata* (Chinese fir) plant species, respectively (Zhou and Jiang 2004; Kuehl et al. 2013).

Because of their environmental benefits, bamboo stands are also known as “natural oxygen bars.” A study by Tan et al. (2010) showed that in China, the concentration of negative oxygen ions in bamboo forest is double in amount than an adjacent woody forest. Li et al. (2003) found that rough surface of a bamboo leaf can catch about 4–8 gm^{-2} of dust. It is also found to reduce noise pollution. A reduction in noise levels by 10 to 15 dB was found in a 40-meter-wide land covered with bamboo plants.

2.6 Biodiversity Conservation

The tender shoots and culms of bamboo serve as food for various types of insects, birds, and animals including giant panda (*Ailuropoda melanoleuca*), bears (*Ursus* spp.), and boars (*Sus scrofa*). The presence of starch and other nutrients makes it attractive food for deer and other forest animals (Li et al. 2003). The presence of high bird population of forests of bamboo in China was reported in literature (Li et al. 2003; Song et al. 2011). Similar observations of the presence of variety of bird species were reported in the bamboo forest portion of Chilean forests as well (Reid et al. 2004).

3 Essential Physicochemical Properties of Bamboo

Physical and chemical properties affect seasoning, durability, and utilization potential of the bamboo culm. The bamboo culm consists of nodes, separating the culm into internodal sections. Nodes and internodes are reported to possess no significant variation in chemical composition (Scurlock et al. 2000). The bark of the culm has epidermal cells of waxy layer (cutin). Vascular bundles consist of vessels and sieve tubes.

3.1 Lignocellulosic Content

In bamboo, the broader lamellae consist of the fibrils oriented with very low angle to the axis of fiber. However, the narrow lamellae are known to show a transverse orientation with higher LC. The wall structure of bamboo fiber, which is polylamellate, provides it resistance to tensile forces and thus bestowed it significantly high tensile strength. Natural fibers with competitive specific tensile strength and stiffness are more in demand than glass fiber and synthetic fibers.

Bamboo culms consist mainly of cellulose, hemicellulose, and lignin (approximately 90%). Cellulose is a fundamental material for all plants. Polymers of cellulose (molecular weight 162) are made up of monomer $C_6H_{10}O_5$. The mean degree of polymerization in bamboo is considered as 10,000 (Fig 5).

Chain and layer lattice of cellulose molecules show an isotropic behavior. Cellulose constituents provide mechanical strength to bamboo. Difference in proximate chemical compositions of bamboo and hardwoods is attributed to difference in alkaline components, ash content (AC), as well as silica contents. Mechanical properties and durability of bamboo species depend on chemical composition of species.

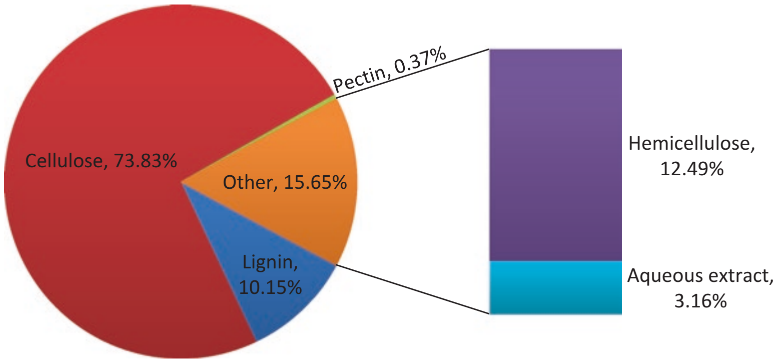

Fig. 5 Constituents of bamboo species. (Wang et al. 2009)

Unlike wood, bamboo lacks rays or knot, beneficial for even distribution of stresses longitudinally (Scurlock et al. 2000).

Chemical extractives of bamboo species are significantly different than wood. Macroscopically graded structure and microscopically graded architecture of fiber distribution provide favorable properties of bamboo.

Literature on chemical constituents of commercially important bamboo species is scanty. Available data of certain bamboo species in this context are compiled in Table 1. The change in geographical conditions and species contributes to difference in properties observed.

3.2 Ash Content

The presence of high amount of silica, calcium, potassium, manganese, and magnesium like inorganic minerals results in high ash content (AC) in bamboo. AC influences the processing of bamboo and has a direct bearing on type and design of processing machinery and tools. AC influences cutting properties, machining operations, and pulp processing properties. Bamboo species investigated in literature were found to have AC between 2.6 and 4.7%. As compared to wood, bamboo is reported to have higher AC. AC of aspen (*Populus* spp.), white oak (*Quercus alba*), and kenaf wood (*Hibiscus*) species contains ash 0.43%, 0.87%, and 1.6–22%, respectively (Ashori 2006). Bamboo species were found to have AC between 3.9 and 5.2%, whereas *Gigantochloa scortechinii* (buluh semantan) species of India contains ash in the range of 1.90– 3.50% (Ganesh 2003). *Bambusa blumeana* (spiny bamboo) species consists of 1.67% AC (Ireana 2010). AC for buluh semantan bamboo, *Gigantochloa levis* (Levis bamboo), *G. brang*, and *G. wrayi* of Malaysia was found to be 2.83%, 1.29%, 1.25%, and 0.88%, respectively (Wahab et al. 2013; Datta et al. 2017). AC was found to be independent of location, nodal and antinodal portions. A positive correlation was found between moisture content and AC. All these studies indicate the range of AC in various bamboo species varied from 0.53 to 4.21%. The lowest AC of *G. wrayi* and *G. brang* makes the processing of bamboo

Table 1 Water, alkali, alcohol-benzene soluble, and AC of various bamboo species

Bamboo species	Ash (%)	Cold-water solubility (%)	Hot-water solubility (%)	Alkali solubility (%)	Alcohol-benzene solubility (%)
Bambusa arundinacea (giant thorny bamboo)	–	9.8 (Kaur et al. 2016a)	11.4 (Kaur et al. 2016a)	27.0 (Kaur et al. 2016a)	3.8[a] (Kaur et al. 2016a)
Bambusa bambos (Indian thorny bamboo)	–	10.0 (Kaur et al. 2016a)	11.2 (Kaur et al. 2016a)	27.4 (Kaur et al. 2016a)	3.6[a] (Kaur et al. 2016a)
Bambusa nutans (Jatia-mokal)	–	7.1 (Kaur et al. 2016a)	8.1 (Kaur et al. 2016a)	28.3 (Kaur et al. 2016a)	4.2[a] (Kaur et al. 2016a)
Bambusa pallida (Jati-banh)	–	11.1 (Kaur et al. 2016)	12.6 (Kaur et al. 2016a)	27.0 (Kaur et al. 2016a)	5.2[a] (Kaur et al. 2016a)
Bambusa tulda (Bengal bamboo)	–	8.1 (Kaur et al. 2016a)	7.8 (Kaur et al. 2016a)	26.1 (Kaur et al. 2016a)	3.2[a] (Kaur et al. 2016a)
Bambusa vulgaris (common bamboo)	4.21 (Subekti et al. 2015)	8.81 (Subekti et al. 2015)	10.22 (Subekti et al. 2015)	23.8 (Subekti et al. 2015)	1.99 (Subekti et al. 2015)
Dendrocalamus asper (solid bamboo)	1.5 (Kamthai 2003); 3.55 (Subekti et al. 2015)	6.4 (Kamthai 2003) 11.34 (Subekti et al. 2015)	9.2 (Kamthai 2003); 9.58 (Subekti et al. 2015)	24.7 (Kamthai 2003; 29.47 (Subekti et al. 2015)	5.5 (Kamthai 2003); 7.49 (Subekti et al. 2015)
Dendrocalamus strictus (male bamboo)	–	6.7 Uttar Pradesh, India; 6.2 Haryana India (Kaur et al. 2016a)	8.4 Uttar Pradesh, India; 8.3 Haryana India (Kaur et al. 2016a)	27.9 Uttar Pradesh, India; 28 Haryana India (Kaur et al. 2016a)	4.2[a] Uttar Pradesh, India; 4.9 Haryana India (Kaur et al. 2016a)
Gigantochloa atter (black bamboo)	1.47 (Subekti et al. 2015)	8.25 (Subekti et al. 2015)	9.63 (Subekti et al. 2015)	24.11 (Subekti et al. 2015)	3.31[a] (Subekti et al. 2015)
Gigantochloa atroviolacea (Java black bamboo)	1.57 (Subekti et al. 2015)	5.91 (Subekti et al. 2015)	7.70 (Subekti et al. 2015)	20.93 (Subekti et al. 2015)	4.51[a] (Subekti et al. 2015)
Gigantochloa apus (string bamboo)	1.57 (Subekti et al. 2015)	7.88	8.18	20.93	3.39[a]
Gigantochloa wrayi	0.53–1.41 (Wahab et al. 2013)	–	–	–	–

(continued)

Table 1 (continued)

Bamboo species	Ash (%)	Cold-water solubility (%)	Hot-water solubility (%)	Alkali solubility (%)	Alcohol-benzene solubility (%)
Pseudosasa amabilis (Tonkin bamboo)	1.38 (Cheng et al. 2015)	–	–	–	–
Pleioblastus chino (Chino bamboo)	1.79 (Cheng et al. 2015)	–	–	–	–

[a]Represents ethanol-toluene solubility

relatively easier. Common bamboo and solid bamboo were found to have relatively higher AC; therefore industrial workers engaged in processing of these bamboo species may encounter problems in processing of the same. Higher AC of these species recommends avoiding the use of these species in industries which require frequent cutting and shaping of the culms.

3.3 Water Solubles

Water solubles are the substances present in cavity cells, fiber cell wall, and cell pores. Cold-water solubility is a measure of the tannins, gums, sugars, and coloring matter in the bamboo. Hot-water solubility provides information about starch content in addition to the above parameters.

Solubility of starch in water at only high temperature makes hot-water-soluble contents higher than cold-water-soluble contents. It is expected that high amount of starch contributes toward higher water-soluble contents. Solid bamboo, *B. pallida*, giant thorny bamboo, and Indian thorny bamboo with higher water solubles may contain higher starch and more vulnerable to degradation (Chew et al. 1992). Cold-water solubility is an indicative parameter for the presence of starch and other sugar components.

Male bamboo species of Uttar Pradesh and Haryana were found to have same cold-water solubility, but hot-water solubility of Haryana species was lower, indicating lower starch content of species in this geographical location (Kaur et al. 2016a). Absorption of water in cement material for production of cement-bonded particle board is affected by chemical content (starch and sugar). The study showed that soaking bamboo chips in water resulted in reduction of its sugar content (less than 0.5%), essential for the manufacture of cement-bonded particle board.

3.4 Alkali Solubility

Solubility in a hot dilute alkali solution (1% solution of NaOH) indicates the extent of decay in a given biomass sample. This includes hemicellulose content and degraded cellulose in biomass sample. Alkali solubility increases in proportion to increase in decay of biomass material. The increased decay results in decreased pulp yield causing severe losses for value-added bamboo products. A few studies are available in literature to evaluate the alkali solubility of bamboo species. Male bamboo species of both Haryana and Uttar Pradesh possessed approximately same alkali solubility. All the bamboo species reported in literature were possessed the alkali solubility between 20.93 and 29.47%. The studies suggest that just after harvesting, the immediate treatment is prerequisite for utilization of bamboo.

Adequate management and efficient storage practices should be followed to avert the degradation of cellulosic material of bamboo caused due to the biotic agents. *G. scortechinii* and Java black bamboo with low alkali solubility are expected to be durable, while solid bamboo and *B. nutans* bamboo species require immediate preservation and treatment.

3.5 Ethanol-Toluene Solubility

The part of material, which is not a part of bamboo's polymeric material, is evaluated using the investigations of the ethanol-toluene extract. Harvesting season and drying affects this constituent of bamboo. Investigation of these extractive contents is highly desirable as they directly affect the quality of pulp produced (Lourenco et al. 2010).

In spite of negative effects associated with higher contents of these extractives on pulp quality and quantity, not much of the studies have been performed to evaluate them. Ethanol-toluene solubility of Indian bamboo species was found in the range of 3.2–5.2%. Solid bamboo was found to possess the highest and lowest alcohol-benzene solubles of 7.49% and 2.5%, respectively (Subekti et al. 2015).

3.6 Starch Content

In general it is believed that the mechanical properties and durability of bamboo species depend on chemical composition of species. Absorption of water in cement material for production of cement-bonded particle board is affected by chemical content (starch and sugar). Starch component in bamboo makes it attractive food for microorganisms like fungi. However investigations performed by Kaur et al. (2016a) on Indian bamboo species revealed no direct correlation between starch content and service life of bamboo culms. Starch content of male bamboo (Uttar Pradesh) was maximum (4.5%), while *B. tulda* (Bihar) has the lowest starch content (1.8%). During decay resistance analysis, all untreated samples exhibited more than 50% of weight loss. *B. tulda* (Bihar) with the lowest starch content (1.8%) was found to be more decayed (weight loss: 57.4%) than male bamboo (Uttar Pradesh) with the highest starch content (4.5%) showing weight loss of 54.3%. *B. pallida* (Karnataka) has 2.8% of starch content, while weight loss by white rot fungi was the maximum for this species.

4 Parameters affecting Physicochemical Properties

The various physicochemical properties of bamboo species vary significantly with change in geographical conditions. Male bamboo species from two different geographical locations was found to have different values of this component solid bamboo species exhibited 5.5% and 7.49% soluble depending on geographical conditions of growth of species (Subekti et al. 2015; Varma et al. 2017).

4.1 Density

Mechanical properties are a function of density. It influences not only shear, compression parallel to grain, but also modulus of elasticity. Decrease in density results in reduced mechanical strength. Bamboo possesses excellent mechanical properties which are correlated with the density. Fiber content and density of bamboo culm varies among different species.

Density is also known to be directly related with tensile strength of species. Scientific investigations on variation of density highlight the variation in property on longitudinal as well as radial basis. Various researches show the variation in density (0.56–0.96 gm/cc) with species was reported in literature (Subekti et al. 2015). Density values of Malaysian bamboo species, common bamboo, *G. scortechinii*, and male bamboo, were reported to be 0.61, 0.63, 0.52–0.67, and 0.65–0.67 gm/cc, respectively (Hamid et al. 2012; Ahmad and Kamke 2003; Hamdan et al. 2009). Solid culm of male bamboo species may provide it more structural strength. This may justify the application of male bamboo species for building and construction industries to bear heavy loads.

4.2 Lignin

Most abundant natural polymer substances present in nature include cellulose, hemicelluloses, and lignin. Plant species like bamboo contains 10–40% of LC on dry weight basis. Lignin is a mononuclear aromatic polymer, often bound to adjacent cellulose fibers to form a lignocellulosic complex, providing strength to the culms. Lignin composed of three units, hydroxyl-phenyl, guaiacyl, and syringyl, which give bamboo a strength in compression, along with structural rigidity and high heating value.

LC of investigated species was found to be in range of 21.5–28.3%. The LC of pine and spruce wood was in the range of 24–27% (Huang et al. 2008). Male bamboo species of both geographical locations, i.e., Haryana and Uttar Pradesh, were found to be rich in LC (Kaur et al. 2016a). Lignin provides resistance against certain microorganisms.

High LC is an undesirable factor in pulp and paper industry as it results in high delignification rates, chemical consumptions, and low pulp yield. Strength of paper produced is directly related to CC of the pulp (Khalil et al. 2010; Kumar et al. 2017).

The carbohydrate content of bamboo is related to durability against microorganisms and service life. Similar to other lignocellulosic materials, cellulose microfibrils of bamboo are embedded in an amorphous matrix of lignin and hemicellulose.

Traditionally quantification of its constituents is performed using wet chemical analysis methods, such as nitrobenzene oxidation, thioacidolysis, derivatization, and reductive cleavage. Although these methods provide valuable and accurate information about these components, they involve long-time duration and many chemical reagents in high quantities, and furthermore they are laborious. Thus, to enhance the large-scale utilization potential of commercial bamboo species, further research for determination of these components in rapid manner is essential. Various sophisticated spectroscopic and chromatographic techniques are used by few researchers to study the detailed structural analysis of type of lignocellulosic components present in species biomass. This includes Fourier-transform infrared spectroscopy as well as nuclear infrared spectroscopic studies (Li et al. 2015). The available studies on quantification of lignin, lignocellulosic, and cellulose components are summarized in Table 2.

4.3 Cellulose

Large variation in cellulose content (CC) is observed in literature. The general range of cellulose in investigated species is between 40.2 and 53.3, maybe because of difference in geographical location, season of harvesting, age, and part of culm investigated.

While Java black bamboo and string bamboo, black bamboo, and male bamboo with high LC are least recommended pulp and paper industry, solid bamboo and common bamboo species with high CC may be considered as the best choice for paper manufacturing industry.

Though pulp and paper industries require information about CC of species selected, very few studies have been found in literature to quantify the same. There is a strong need to quantify extractives and components of bamboo species not reported in these studies.

4.4 Starch

The presence of sufficient quantities of starch is prerequisite for insect and microbial attacks on the bamboo culm. The most appropriate age of harvesting bamboo is reported to be 3 years with the lowest starch content. The study of the radial distribution of starch in the culm shows that the inner portion of the Indian thorny bamboo culm was found to be richer in starch (6.6%) content as compared to the outer portion (4.8%) for the middle section. It is also reported that the variation of starch content from 1.5 to 4.8% and 5.2 to 8.5% bases top portion, respectively.

There exists a negative correlation between extractive contents and pulp yield. Higher starch content of male bamboo species from Allahabad, India, may cause the

Table 2 Starch, density, lignin, lignocellulose, and CC of bamboo species

Bamboo species	Starch (%)	Density (gm/cc)	Lignin (%)	Lignocellulose (%)	Cellulose (%)
B. arundinacea	2.0 (Kaur et al. 2016a)	–	26.5 (Kaur et al. 2016a)	47.7 (Kaur et al. 2016a)	–
B. balcooa	–	0.81 (Naik 2009); 0.8–0.9 (Saikia et al. 2015)	20.5–23.4 (Saikia et al. 2015)	78.69 (Naik 2009)	40.2–44.5 (Saikia et al. 2015)
B. bambos	–	0.71 (Naik 2009)	–	74.96 (Naik 2009)	–
B. bambos	2.0 (Kaur et al. 2016a)	–	21.5 (Kaur et al. 2016a)	50.5 (Kaur et al. 2016a)	–
B. blumeana	–	–	21.6 (Nor-Aziha and Azmy 1991)	–	–
B. nutans	1.9 (Kaur et al. 2016a)	0.89 (Naik 2009)	26 (Kaur et al. 2016a)	51.6 (Kaur et al. 2016a) 69.25 (Naik 2009)	–
B. pallida	2.8 (Kaur et al. 2016a)	–	20 (Kaur et al. 2016a)	46.5 (Kaur et al. 2016a)	–
B. tulda	1.8 (Kaur et al. 2016a)	0.91 (Naik 2009); 0.68–0.8 (Saikia et al. 2015)	24 (Kaur et al. 2016a); 19.8–21.9 (Saikia et al. 2015)	56.2 (Kaur et al. 2016a); 77.14 (Naik 2009)	38.9–42.5 (Saikia et al. 2015)
B. vulgaris	–	–	21.9 (Subekti et al. 2015)	–	53.3 (Subekti et al. 2015)
D. asper	–	–	28.5 (Kamthai 2003); 24.5 (Subekti et al. 2015)	–	51.2 (Subekti et al. 2015)
D. giganteus	–	0.74 (Naik 2009); 0.65–0.87 (Saikia et al. 2015)	18–19.2 (Saikia et al. 2015)	78.27 (Naik 2009)	40.3–42.3 (Saikia et al. 2015)
D. hamiltonii (Hamilton's bamboo)	3.76 (Naik 2009)	0.59 (Naik 2009)	–	79.04 (Naik 2009)	–

(continued)

Table 2 (continued)

Bamboo species	Starch (%)	Density (gm/cc)	Lignin (%)	Lignocellulose (%)	Cellulose (%)
D. strictus	2.5 Haryana (India); 4.5 Uttar Pradesh (UP), India (Kaur et al. 2016a)	–	27.0 Haryana (India) (Kaur et al. 2016); 25 UP (India) (Kaur et al. 2016a)	53.4 Haryana (India) (Kaur et al. 2016a); 53.6 UP (India) (Kaur et al. 2016a)	–
G. apus	–	–	24.8 (Subekti et al. 2015)	–	49.6 (Subekti et al. 2015)
G. atroviolacea	–	–	26.7 (Subekti et al. 2015)	–	49.6 (Subekti et al. 2015)
G. atter	–	–	27.3 (Subekti et al. 2015)	–	49.8
G. macrostachya (Phai bamboo)	0.72 (Naik 2009)	0.96 (Naik 2009)	–	78.07 (Naik 2009)	–
Melocanna bambusoides (Muli bamboo)	0.10 (Naik 2009)	0.72 (Naik 2009)	–	80.80 (Naik 2009)	–
Phyllostachys bambusoides (madake bamboo)	2.1% (Peng et al. 2011)	0.73 (Naik 2009)	–	85.21 (Naik 2009)	–
Phyllostachys pubescens (moso bamboo)	2.12–3.29 (Okahisa et al. 2006)	–	23.6 (Li et al. 2007)	–	–

increased consumption of pulping chemicals, corrosion of handling equipment, low pulp yield, and pulp brightness (Table 2). This discourages the use of the same for pulp and paper industry. A few traces of starch in Bengal bamboo, *B. balcooa* (balcooa bamboo), Indian thorny bamboo, *B. nutans*, *D. giganteus* (dragon bamboo), and madake bamboo species were reported (Liese and Kumar 2003). These species may be recommended for the use of production of paper from pulp.

5 Durability of Various Bamboo Species

Environmental and financial comparison of bamboo with other building material shows its competitiveness. However, in spite of all these advantages, it is still considered as a rural resource. This is because of shorter life span of bamboo and its products. Studies indicate that due to problem of insect-pest attack, steel is

Fig. 6 Decay of untreated bamboo (IIT Delhi, India) in about 5 years of installation

considered over bamboo as choice for building bridges in Europe. Though there are mammoth bamboo forests globally, the resources are exhausting due to excessive harvesting to meet demands of paper-pulp industry. Therefore, in order to achieve the maximum utilization potential for this natural resource, there is a strong need for the active and systematic preservation practice. Along with this, available resources should also be used wisely with minimum wastage (Janssen 2000).

Bamboo with sufficient amount of starch and negligible amount of toxic constituents is susceptible to attack by a variety of organisms including fungi and termites. Natural durability of bamboo species is defined as “the resistance of bamboo to be attacked by bamboo-destroying organisms.” Depending on the species of bamboo, climatic conditions of growth, harvesting season, and duration of storage, its average life span is known to be 1 to 3 years only.

In addition to this, the inherited resistance is affected by temperature, humidity, and the condition of the cell walls. Figure 6 shows degradation of bamboo culms by microorganisms and insects. For efficient utilization, knowledge about its physicochemical constituents and durability is essential.

6 Factors Resulting in Poor Life Span

Type and extent of microbial attack on bamboo are strongly dependent on moisture condition which depends on type of species, conditions of storage, ambient temperature, and humidity (Kaur et al. 2016d). Bamboo is stored outdoors for up to 1 year. Bamboo species are associated with constraints of limited service life, which is even shorter than timber (Subekti et al. 2015). Among these reported species, Bengal bamboo was reported to be most durable with service life less than 2 years. Biotic factors include various microorganisms like fungi and insects like termite. Abiotic factors like weathering, fire, improper handling during storage, cracks, and splits add to deterioration of bamboo culms.

There are basically two types of factors that affect the quality of bamboo culms in service (Fig. 7). Biotic factors include the resistance of culms to various microorganisms and insects attacking the culms alone or in succession. Bamboo is one of the strongest material, but certain non-biotic factors also affect its quality. Abiotic factors of decay of bamboo include climate of the place where bamboo culms are stored. Environmental factors like heat and sunlight (ultraviolet) affect the outdoor service life of bamboo culms. Heat and ultraviolet radiations of sun weather the harvested culm through photooxidation process. Sun-heat causes checks in bamboo leading to development of cracks in culms. Ultraviolet radiations of sun break down the lignocellulosic bond. The surface turns gray and coarse. Rain, abrasion by wind, and fluctuating temperature and moisture accelerate the weathering process and reduce durability of bamboo species. Major chemical constituents of biomass are affected by degradation (Poletto et al. 2012). Cracks and splits may occur due to frequent exposure of culms to wetting and drying cycles of weather conditions.

Under particular conditions, bamboos are targeted by number of organisms. Attack by fungal species is one of the most common reasons of its destruction. Fungi grow in a conducive environment due to specific combinations of moisture, temperature, aerobic conditions, etc. In tropical regions and temperate regions, termites and fungus are the chief destructor, respectively. The decay pattern of fungus follows a completely different mechanism than other insects. Thus the method of control is also dependent on source of decay.

Biotic factors include various types of fungi. Brown rot fungi mainly *Oligoporus placenta* and white rot fungi like *Trametes versicolor*, bacteria, and termites attack bamboo species. Fungi like *T. versicolor* and *P. versicolor* result in more than 50% of destruction of the culm under storage conditions (Schmidt et al. 2011; Kaur et al. 2016a; Yadav et al. 2018).

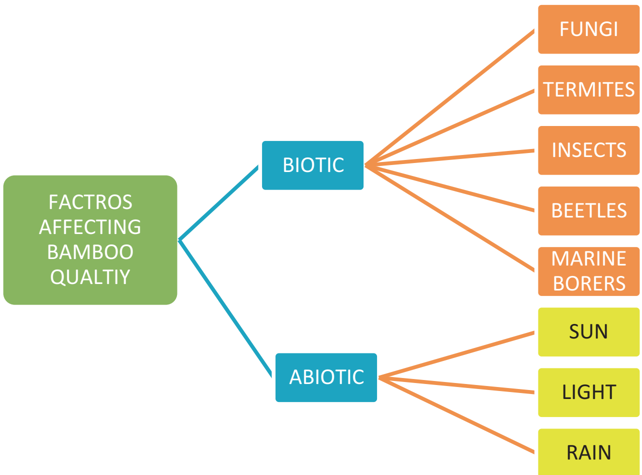

Fig. 7 Factors affecting the quality of bamboo. (Kaur et al. 2016d)

7 Storage and Attack of Fungal Infestation

Decay caused by fungi is the major source of quality loss in both timber and bamboo biomass. Poor natural durability of bamboo against fungi is reported in literature (Xu et al. 2013). Resistance against various kinds of fungi depends on species, culm part, and moisture content of bamboo culm (Schmidt et al. 2013). All fungi produce spores (which are like tiny seeds) that are dispersed by wind and water. The spores can infect moist bamboo during storage, processing, and use. All fungi have certain basic requirements. Optimum conditions for fungi growth include temperature about 20 °C to 30 °C and moisture below 19%. Adequate supply of oxygen and food source like cellulose, hemicellulose, lignin, and starch is required for fungi to grow and multiply.

Fungi consist of a large heterogeneous group of heterothallic organisms living as saprophytes or parasites or in association with other organisms as symbionts. They are ubiquitous, found everywhere in air, soil, water, plant, or animal bodies.

Based on mode of nutrition, fungi are grouped as white rot, brown rot, and soft rot. As the name suggests, the white rot fungal attack causes a bleach appearance because it consumes both lignin and cellulose. Brown rot fungi feed mainly on cellulose. It metabolizes carbohydrate fractions of wood and bamboo, thus affecting the strength. Depolymerization of cellulose fraction takes place, resulting in lower pulp yield. Permanganate number of this type of bamboo is so high that the pulp is different to bleachable (Khalil et al. 2010).

Fungi growth on building materials not only causes material damage but also is hazardous to human health (Li et al. 2015). Fungi mycelial growth causes more damage to buildings than spores. Spores and hyphal fragments, released from fungal biomass, have associated allergies, toxicity, and infections (Torvinen et al. 2006). Contaminated building materials with fungal infestation are a source of contaminated surrounding. The microbially produced volatile organic compounds can also affect the quality of surrounding air, causing sick building symptoms.

There is a large variation in durability reported in the studies. The methods used by these investigators are different. Difference in duration and method of investigation might have contributed to wide variation in durability of these species (Table 3).

Age, height of culm, and period of harvesting also contribute to better service life of the culm. *G. scortechinii* and moso bamboo with weight loss less than 10% against decaying fungi can be considered as highly durable species. The storing and management of these species can be done with ease (Wei et al. 2013).

Bamboo species exhibited less destruction by fungi as compared to wood species. However, *B. nutans*, *B. tulda*, and *B. pallida* bamboo species with loss of more than 55% of weight under fungal infestation conditions are reported to be highly fungal susceptible species.

Table 3 Antifungal decay resistance of a few bamboo species

Species	Fungi	Weight loss %	Test method
B. blumeana	Soft rot fungi	31.9	ASTM D2017 for 8 weeks (Adrianus et al. 2010)
B. blumeana	Soft rot fungi	27.8	ASTM D2017 for 8 weeks (Adrianus et al. 2010)
B. maculate	*T. versicolor*	0.5–1.5	EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
B. arundinacea	*P. versicolor*	55.7	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
B. bambos	*P. versicolor*	56.9	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
B. nutans	*P. versicolor*	58.2	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
B. pallida	*P. versicolor*	59.2	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
B. tulda	*P. versicolor*	57.4	ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
D. asper	*T. versicolor*	8.2	EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
D. asper	*P. sanguineus*	19.0	Kolle-flask method (Suprapti 2010)
D. strictus	*P. versicolor*	54.1	Haryana species (India) ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
D. strictus	*P. versicolor*	54.3	Uttarakhand species (India) ASTM D 1413 for 12 weeks (Kaur et al. 2016a)
G. angustifolia	*T. versicolor*	2.3	EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
G. atroviolacea	*T. palustris*	21.0	Kolle-flask method (Suprapti 2010)
G. atroviolacea	*T. versicolor*	10.4	EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
G. apus	*Polyporus* sp.	21.7	Kolle-flask method (Suprapti 2010)
G. atroviolacea	*T. versicolor*	45.7–55.4	EN 113 (1996) (Schmidt et al. 2011)
G. scortechinii	*C. versicolor*	5.3	ASTM D 2017-81 (1986) for 8 weeks (Hamid et al. 2012)
P. pubescens	*T. versicolor*	12.3	Germany species, EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
P. pubescens	*T. versicolor*	15.3	Chinese species, EN 350-1 (1996) for 16 weeks (Wei et al. 2013)
P. pubescens	*C. globosum*	36.9–39.7	EN 113 (1996) (Schmidt et al. 2011)
P. pubescens	*F. palustris*	8.6–9.6	Japanese Industrial Standards (JIS) K-1571-2004 for 12 weeks (Okahisa et al. 2006)

(continued)

Table 3 (continued)

Species	Fungi	Weight loss %	Test method
P. pubescens	*T. versicolor*	10.8–12.0	Japanese Industrial Standards (JIS) K-1571-2004 for 12 weeks (Okahisa et al. 2006)
Malaysian bamboo species	*C. versicolor*	0–36	Incubation with fungi at 22 °C for 8 weeks (Hamid et al. 2012)

8 Resistance to Termites and Insects

Termites are a type of most timber damaging insects (Isoptera) found in 2500 species, with 300 of them labelled as pests. They exist in families and subfamilies, with nests underground, or on hollow of wood or mounds. Past behavior and damaging pattern can help to identify the type of pest species. Harvester termites are found in dry regions, live underground, and are difficult to spot.

Various studies have reported the destruction of bamboo culms because of severe termite infestation. Subterranean termites are major species of termite causing immense destruction during storage. They are social insects, living in colonies of workers, soldiers, and reproductive. The worker termites are whitish in color, are wingless, and are numerous in numbers. Soldiers are also like workers with brown heads and mandibles. They are the protector of colonies. Reproductive function in colony is performed by king and queen termites.

Termites are most successful of all the social insects because of their long life span. They depend entirely over wood and woody tissues for survival. Termite attack is visible on bamboo species, depending on its constituents and properties. Factors like density have a significant effect on bamboo's resistance to fragmentation by termite's attack. Wood and other lignocellulosic biomass are the major food source of termites. The subterranean termite species are the most common species of termite which are most widely distributed and most destructive.

Different physical, mechanical, and chemical properties of wood provide resistance against termite. It is believed that the presence of carbohydrate in wood and bamboo makes it susceptible to termite attack. As termites use cellulose as food, products like paper, fabrics, and woody structures are readily destroyed by them. Hence, a constant effort is being made world over to protect them from destruction.

Termites are destroyers of wood and wooden products in human homes, building materials, forests, and other commercial products (Peralta et al. 2003). Economic losses due to termite attacks include costs of repair and control. Cellulosic materials used in buildings are easy target for termite species. In Indonesia, US $ 200–300 million in 2000 were lost due to termite attack on wood in buildings (Yoshimura and Tsunoda 2004). In India, about 35 species are known to be damaging agricultural crops and buildings (Choudhury et al. 2017; Ashoka et al. 2017).

The termite degradation resistance was found to be independent of season and height of the culm. The yearly average mortalities of the workers and soldiers were 33.2–43.6% and 62.8–69.6% for 2 years old, respectively (Table 4).

Table 4 Termite damage to bamboo species against termite

Bamboo species	Mean percent mass loss (%)	Method
G. angustifolia	24.52	No choice test (Hapukotuwa and Grace 2011)
B. hirose	20.97	
D. latiflorus	21.04	
D. brandisii	16.76	
B. oldhamii	15.73	
G. pseudoarundinacea	12.96	
D. asper	5.3	JIS E1-09 for 3 weeks (Subekti et al. 2015)
B. vulgaris	8.2	
G. atter	8.74	
G. atroviolacea	5.73	
G. apus	6.85	
P. densiflora	12.86	

Studies on the details of weight loss of bamboo species against termites are very limited. Available studies show the bamboo is an easily perishable material. They are able to decompose cellulose, along with lignin, ash, and silica. Termite resistance was found to be independent of oligosaccharide and polysaccharide contents. The presence of nitrogen, ash, silica, and LC may affect the resistance of bamboo against termites. Termite resistance was found to be inversely related to lignin content. It was found that higher LC leads to greater termite resistance. As termites have a substantial preference for nitrogen-rich food, high nitrogen content causes higher damage by termite infestations. Termite durability was found to be independent of AC. The presence of higher silica in bamboo leads to lower termite damage (Dhawan et al. 2007).

Gigantochloa pseudoarundinacea (maxima bamboo) exhibited lowest weight loss of 12.96% against termites using no-choice test (Hapukotuwa and Grace 2011). Three-week termite resistance tests displayed the decay of solid bamboo as the most termite-resistant bamboo species (Subekti et al. 2015).

The investigation also highlighted the negative correlation between the LC and termite resistance. Black bamboo species with LC higher than Java black bamboo, solid bamboo, and common bamboo also reported to exhibit the higher resistance to termite attack. In addition to this, studies also indicated the positive correlation between CCs with termite resistance. Common bamboo samples with higher CC than solid bamboo, black bamboo, Java black bamboo, and string bamboo were heavily damaged by termites.

Resistance to fungi is regarded as absolutely essential to all fields of biomass applications. The strength properties of buildings and pulp obtained from bamboo attacked by decay fungi and termites were lower than those made from stained and decayed bamboo. Hence it is not wise to store these bamboos in areas that are warm and humid.

9 Bamboo as Multipurpose Species

In today's era, global concern for sustainable future is promoting users to switch to bamboo culms for multiple purposes.

9.1 Traditional Uses of Bamboo

Field of applications of bamboo varies from vessels, fences, poles, and musical instruments like flute to food and fodder. Bamboo ropes, mats, baskets, fishing nets, ladders, fans, brooms, lamps, thatching and roofing, bows and arrows, handicrafts, and toys were quite common among rural communities. Chemical products like beer, energy drink, air freshener, and deodorizer add value to bamboo culms.

9.2 Bamboo as Fuel

Biomass is drawing global attention as an attractive alternative renewable energy source, which, using various thermochemical and biochemical conversion techniques, can be easily converted into high-energy content fuel. Combustion, pyrolysis, gasification and liquefaction processes, digestion, and fermentation are the most commonly used conversion techniques to reduce our dependency on fossil fuel. At present, biomass energy shares a significant proportion in total energy generation of the world, which is around 14% of energy supply, after coal, oil, and natural gas (Asif and Muneer 2007). Bamboo, being highly renewable, is the most preferred source for the generation of bioenergy (Scurlock et al. 2000). Since biomass per hectare of bamboo is higher than wood, it has relatively greater potential to substitute wood for bioenergy generation.

There are a few reported case studies, where bamboo is used successfully for power production in many countries (INBAR report 2012), especially in Indian states (Assam, Manipur, and Mizoram) where bamboo is used for electricity generation. Kumar and Chandrashekar (2014) reported balcooa bamboo with high basic density (0.63 g/cm^{-3}), low AC (1.7%), high fixed C content (21.1%), high calorific value (19.6 MJ/kg^{-1}), and low concentrations of potassium (20.6%) and chlorine (0.1%) as the most suitable bamboo species for energy generation.

9.3 Bamboo as Food

Bamboo shoots being rich source of protein, potassium, carbohydrate, dietary fibers, vitamins, and active materials provide nutritious food to the local community. Consumption pattern of bamboo shoots is seasonal and region-specific. Soft, tender bamboo shoots are consumed as vegetables and pickles. Bamboo plays a substantial role to provide the food and nutritional security to the people of bamboo-growing areas. Various traditional techniques are used to ferment bamboo shoots to improve their shelf life and delicacy (Roy et al. 2017). Various medicinal benefits are known to be associated with bamboo shoots. Ethno-pharmacological uses of bamboo include its anticancerous, antidiabetic, and antiulcer activity (Sangeetha et al. 2015).

9.4 Bamboo as Medicine

Bamboo salt, vinegar, and extracts are being used to control diseases like diabetes and cholesterol. Hypertension, sweating, and paralysis can be treated using bamboo. Various parts of giant thorny bamboo (leaf, root, shoot, and seed) are known to have anti-inflammatory, antiulcer, antioxidant, anthelmintic, and astringent activity. Ringworm can be treated using root (burnt root), while skin eruptions can be cured using bark of this tree. Antileprotic and anticoagulation activities of its leaf make it useful for treatment of hemoptysis.

High surface area of bamboo charcoal gives it absorption properties better than wood charcoal, which can be used for numerous biomedical applications including absorption of toxin from blood. Nanoparticles ($NiO.5ZnO.5Fe_2O_4$) that coated bamboo charcoal was found to possess microwave and infrared energy absorption properties. Bamboo charcoal's amalgamation with long with silver nanoparticle resulted in microwave absorption properties. The bamboo charcoal was found to be better adsorbent as well. Bamboo charcoal also has antimicrobial and antifungal activities. It can also be used to protect neurons from oxidative stress. Indian thorny bamboo leaves extract can be used for the most common bacterial diseases (Poletto et al. 2012). Bamboo shoots also help to reduce weight loss and are anti-inflammatory (Hossain et al. 2015).

9.5 Bamboo as Structural Element

Bamboo is a unique creation of nature. The lightweight functionally graded structure composite nature of bamboo culm, made up of axial cellulose fibers, makes it ideal for earthquake-resistant structures. Bamboo with compressive strength double than concrete, shear stress higher than wood, and tensile strength equal to steel is one the strongest building material. Specific properties of bamboo are given in Table 5.

Table 5 Specific properties of bamboo (Shah et al. 2013)

Property	Value
Specific gravity	0.57–0.65
Bond stress	5.6 kg/cm^2
Safe working stress in shear	115–180 kg/cm^2
Safe working stress in compression	105 kg/cm^2
Ultimate compressive stress	794–864 kg/cm^2
Modulus of elasticity	1.5–1.0 × 105 kg/cm^2

Certain added advantages of bamboo as building material include wider span and ease of curvability without breaking (Nurdiah 2016). It is reported in literature that the buildings with bamboo as construction material for the roof top are energy efficient. This reduces the temperature of top floor of building and makes it a comfort zone during hot months of summer. Hoang et al. (2010) reported the effectiveness of bamboo buildings to provide better inside air quality with less ozone level indoors.

9.6 Pulp and Paper

Increasing human population, documentation, rising literacy rate, and improving economic resources have resulted in the rapid growth of pulp and paper industry. Traditionally, wood and timbers were generally used for the manufacture of pulp for the production of paper worldwide. However, the severe problem of deforestation and agricultural waste disposal problems has prompted researchers to look for the alternatives. Non-woody plants like bamboo hold a good opportunity in this field.

About 18 species of bamboo are reported to useful for pulp and paper industry. Bamboo is used for the preparation of printing and writing paper, newsprint substitute, wrapping, bag paper, etc. (Hammett et al. 2001). CC in bamboo (40–50%) is comparable to softwoods (40–52%) and hardwoods (39–56%). Thus cellulosic fibers for paper industry can be obtained from it. In addition to this, it is also useful for the production of ethanol and starch granules for saccharification.

One of the latest studies performed by Sugesty et al. (2015) showed that dragon bamboo and *Gigantochloa robusta* (tropical timber bamboo) are highly suitable for the production of pulp for rayon fiber. *D. brandisii* (velvet leaf bamboo) culms are also reported to be suitable for production of pulp fibers.

10 Bamboo and Livelihood Opportunities: Indian Perspective

Bamboo has been used by mankind since ancient times and now holds a strong capacity to provide income for billions of people every day, particularly in rural areas (Lobovikov et al. 2005; Song et al. 2011).

In fact, with wide range of applications, bamboo species specifically favored for reforestation and forest rehabilitation. Given the fact that manufacturing different products using bamboo can be a zero waste process, they have 100% utilization capability, which is only 20% in case of a wood species (Lobovikov et al. 2012). Processing of bamboo being simple requires no special skill and equipment, leading to low initial investment. Hollow internal structure of bamboo culms makes it lightweight, easy to work with, and easy to transport. Bamboo plant is also found to be an excellent source as C sink and effective in mitigation of greenhouse effect (Bhalla et al. 2008; Ram and Meena 2014).

Table 6 Market demand of bamboo in various applications in India

Bamboo item	Market size 2003 (Rupees crore)	Market potential 2015 (Rupees crore)
Shoots	5	300
Timber substitution	10,000	30,000
Plyboard	200	500
Plyboard for truck, railways	1000	3400
Bamboo mat boards	–	3908
Bamboo flooring	100 for export, 100 for domestic	1950
Pulp	100	2088
Furniture	380	3265
Scaffolding	–	861
Housing	–	1163
Road	–	274
Miscellaneous (pencil, match box, etc.)	394	600

Adopted: Kumar and Tanya (2015)

With about 1500 commercial applications mentioned in literature (Scurlock et al. 2000), it captures a significant share in global market about US $7 billion (Lobovikov et al. 2012). Bamboo is commonly found in Africa, Asia, some parts of Europe, and America. India is rich in bamboo resources accounting 13.96 million hectares forest area with 123 species in 23 genera (FSI report 2011). In India, they are widely distributed, especially in semidry and dry zone along plains and hilly tracts, usually up to an altitude of 1000 meters. North-Eastern Indian states covering a major portion and diversity of bamboo species are also popularly known as "Bamboo Paradise of India" (Goyal and Brahma 2014). It has been reported that in the state of Assam, bamboo forest occupies an area of 1813 km^2 out of total geographical area of 78,438 km^2 (Sharma et al. 2010).

India, China, and Myanmar together constitute ~ 80% world's bamboo forest. Although 45% of the world's bamboo production is shared by India, its share in global market is only 4.5% (Mehra and Mehra 2007). This is mainly due to lack of proper postharvest management and preservation techniques of bamboo culms. Table 6 shows market share of various categories of bamboo products.

India being a developing country has vast potential to utilize bamboo for multiple applications. Bamboo can help to provide not only food security but also employment opportunities to people of India. The wide distribution of Indian bamboo species shows the enormous potential it possesses to develop bamboo-based industries in India. Application of property-specific bamboo species can help to achieve the maximum utilization capability to the Indian bamboo species. Socio-environmental values associated with bamboo make it an alternative material for housing. Excellent flexibility makes it ideal for earthquake-resistant structures. Building bamboo houses in earthquake prone areas of Gujarat and landslide-affected areas of hilly region can provide economically feasible safe houses to the society.

Providing training on advanced equipment, making finance easy to the viable projects, and linking these projects to the markets can help in creation of employment opportunities to the bamboo artisans and improve their socioeconomic status. Development of new products using engineered bamboo may give rise to new dimension of rural economy from abundantly available and lying unused bamboo biomass in rural areas.

11 Conclusion

Bamboo with capability to grow effortlessly on wasteland is emerging as a more suitable alternative to wood, metal, steel, and plastic. Considering the fast growth rate, high tensile strength, and low weight to height ratio, the highest emphasis should be given to its wider utilization. Major bamboo-producing countries include Asian countries, mainly India, China, and Indonesia. Present chapter highlights the variation in not only major constituents like lignin and cellulose but also minor constituents like ash, starch, alkali, and water-soluble contents. These studies emphasize the fact that male bamboo species with solid culm and relatively high lignin density is the most suitable for load-bearing applications especially in building and construction industries. Starch content varies significantly with species from 1.5 to 4.8%. Bamboo species like *B. nutans*, *B. tolda*, and *B. pallida* were reported to be highly fungal susceptible species, with the loss of more than 55% of total weight under fungal attack. The studies urge the necessity of preservation and treatment of bamboo under storage conditions to pave the way forward for efficient resource utilization from the bamboo forests available on all continents.

12 Future Prospects

Bamboo no doubt is a very promising material with numerous species found all over the world. The engineering properties of bamboo have helped it to emerge as a "Material of Future." It is a unique creation of nature with lightweight functionally graded structure composite nature, made up of axial cellulose fibers in a lignin matrix, resulting in high strength both in tension and compression with good laminar shear. However, short life span of bamboo (1–3 years) and fast deterioration under storage conditions put serious constraints on bamboo utilization as structural elements.

Studies on the physicochemical properties are important for the selection of suitable bamboo for its multiple purpose uses. Most of the studies that have been reviewed depict the fact that the distribution and contents of extractives, cellulose, hemicellulose, and lignin remarkably affect its processing properties. Complete characterization of any bamboo species is not available in literature. The review of properties of bamboo species recommends the choice of bamboo species according to the end use. Unavailability of characterization data is a major hindrance to enhance utilization potential of bamboo species.

A significant variation of some properties exists among species. Male bamboo species from different geographical locations have marked differences in their properties. Bamboo species showed marked difference in AC, viz., male bamboo (Haryana) 2.6% and giant thorny bamboo (Uttar Pradesh) (8.1%). Density of all the species reported in literature was found to vary the most. Male bamboo species were found to be rich in LC. Both these factors make this species the righteous material for building and construction applications. *B. pllaida* was low in lignin (20%) and ligno-CC (46.5%), which can be considered as a good choice for paper industry. Characterization of commercially important bamboo species would help in preparing guidelines to choose species as per requirement. Decay resistance analysis showed loss of strength by fungi and termites the most. It is expected that in addition to starch other factors like storage conditions, moisture content, and geographical conditions have contributed toward fungal decay resistance of these species. These studies may give rise to a new dimension of economy from abundantly available and lying unused bamboo biomass globally.

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Sustainable Forestry Under Changing Climate

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Abstract

Climatic perturbation is the major event in the present era that has put the survivality of human civilization under severe threat. Forests are natural boon for us to combat the mega event of climate change. Apart from mitigating climate change, the forests are providing livelihood for community stakeholders, meet up energy demand, provide fodder and fuel and produce various non-timber forest products (NTFPs). Consideration of different multidimensional role of forest is essential for survivality of human civilization. As per the Intergovernmental Panel on Climate Change (IPCC), mitigating climate change through forest appears to be up to 14.0% at various sectors. On the other hand, forests are supporting livelihood security for more than 300 million people of India and meet the energy demand of rural India up to 40.0%, and to provide support for domesticated animals up to one-third. But the existence of forest is under threat due to the rapid growth of human civilization, resource dependency and unsustainable use of forest resources. Therefore, climate change is showing its impact over forests at various levels such as in the form of productive traits, C (carbon) dynamics, vegetation shift and depletion of soil resources. To combat such problems, sustainable forest management (SFM) is a suitable answer as it addresses multidimensional way by reducing resource dependency on one hand and promoting livelihood option for forest dwellers on the other hand. This chapter deals with SFM practices under the changing scenario of climate change. SFM promotes increase in forest cover which further helps to combat and adapt to climate change events. In this way SFM becomes an integrated approach of sustainable management and conservation of natural resources.

Keywords

Biodiversity · Climate change · C dynamics · SFM · Soil resource

Abbreviations

AFOLU	Agriculture forestry and other land use
C	Carbon
CO_2	Carbon dioxide
FAO	Food and Agriculture Organization
FOLU	Forestry and other land use
GHGs	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
N	Nitrogen
NFP	National Forest Policy
NTFPs	Non-timber forest products
OC	Organic carbon
OM	Organic matter
REDD	Reducing emissions from deforestation and forest degradation
SFM	Sustainable forest management

1 Introduction

Forest resource nowadays has become the most scarce resource due to its higher amount of anthropogenic pressure. Mostly the resource dependency of the forest-dwelling community as well as people living in the forest fringes has promoted a higher level of forestland degradation in the recent decades. Forests have multifaceted benefits for the entire human civilization such as economic benefits, ecological benefits, environmental benefits and sociocultural benefits (FAO 2006; Jhariya 2017; Jhariya and Yadav 2018). As a consequence of that, the urgent need for forest conservation has come into the forefront. Forest conservation not only benefits the forest-dwelling communities, but also on a broader scale, it promotes conservation of biodiversity (Jhariya and Raj 2014).

Now on a global scale, forest regulates climate and hydrological cycle and also mediates proper cycling of nutrients. Therefore, forests act as global carbon (C) sink as well as sink for other greenhouse gases (GHGs). Forest has holistic approach in terms of maintaining GHG budget through C dynamics in vegetation and soil, providing biomass as an alternative for fossil fuel and also as raw materials that can produce higher energy for industrial purpose. Forest tends to actively participate in the hydrological process of the nature by promoting rainfall, interception of precipitation as well as sometimes promoting water conservation. Forests often serve as an effective pollutant remover from the atmosphere through moistening and filtering activity. Forest has got some protective action in terms of erosion prevention and desertification (Heal 2000).

As forest is a key resource from an economic perspective, maintaining sustainability is the need of the hour. This has generated the origin of sustainable forest management (SFM). It harbours the three dimensions of sustainability, i.e. economic dimension through sustainable harvesting, ecological dimension through maintaining the integrity of forest ecosystem and social dimension through socio-economic upliftment of rural livelihood. The world is moving towards a low C economy as was mentioned in the agenda of United Nations 2030 vision. This would promote effective management towards sustainable utilization of resources present over the earth's surface. Climatic perturbation is the biggest threat for mankind nowadays. From combating perspective, SFM would help the society to build a sustainable world.

Climate and forest are intricately related with each other. This fact is further proved by the presence of different types of forest on the global scale depending upon the climatic nature. Again climatic changes are too severe for the well-being of vegetation for a particular area (Raj et al. 2018a; Jhariya et al. 2018; Meena et al. 2016). Therefore, proper adaptation needs to be incorporated in the system of SFM. SFM can be achieved through sustainable utilization of resource adopting climatic mitigatory measures under climatic perturbation in the upcoming century.

Climate change and forest together are such a complex issue that multidimensional problems reorient between the two. For instance, climate change alters forest configuration, and forestland degradation produces up to 20% carbon dioxide (CO_2) emission globally. On the other hand, forests provide opportunities by acting as GHG sink for mitigating climate change. Perturbations through climate change on forest ecosystem lead to biodiversity loss, loss of biomass and reduced capacity of forest regeneration (Raj et al. 2018a).

This chapter deals with various aspects about the interrelationship of climate change with forest, impact of climate change over forest and SFM and its consequences.

2 Interrelationship Between Forest and Climate Change

Globally climate change has been found to be intricately related with forest ecosystem producing variable responses. The major impact that climate change imposes includes alteration in the growth as well as the C cycle. During the past century, scientific exploration has revealed that climate change can be indicated through alteration of composition of species and changing pattern of growth in diverse type of forest ecosystems. Under changing climate, forest management is the biggest challenge as it may magnify the negative impacts on forest ecosystem. For example, climatic elements such as precipitation and temperature regime alteration may prove to be critical for forest development. The major influence played by forest is in the form of biomass production and ecosystem resilience, and storage of CO_2 may be hindered unless climatic considerations are considered in case of tree growth parameters (Jhariya 2014; D'Aprile et al. 2015; Berndes et al. 2016; Dhakal et al. 2016). The opposite side of the coin includes creating favourable climate for maximum growth leading to higher wood production and more storage of C (Fig. 1).

Globally it was found that extreme climatic event imposes significant influence over the distribution pattern of vegetation. As climate and forests are intricately related with each other, forest imposes its influence over climate through changes in the land surface reflectivity, roughness and conductivity. Under climate change scenario, water stress condition imposes a significant influence over the species composition of forests (Table 1). For example, the forest community is dominated by shrubs/grassland instead of trees due to higher vulnerability due to root length and fire hazards (Jhariya 2017). It has been reported that temperature decrease makes taller trees much vulnerable in comparison to ground vegetation. Under extreme cold conditions such as polar region and alpine ecosystem, mosses and lichens reflect sparse presence (Whittaker 1975).

In the Asian subcontinent, climate change has imposed severe impact on forests through changes in the phenology, rate of growth, species distribution and composition and forest degradation through permafrost. The situation would be further worse in the twenty-first century. For instance, trees of boreal biome will act as invasive species for arctic biome. On the other hand, evergreen vegetation of conifers would move towards larch forests of deciduous nature. However there is a knowledge gap in terms of vegetational change on lowland tropics influenced by climatic variability. From a faunal perspective, climatic variation would also severely impact directly and indirectly due to loss of suitable habitat (IPCC 2014).

Vegetation of coastal zone is also under severe stress of climate change. It has been observed that mangrove plantation of the coastal region cannot withstand

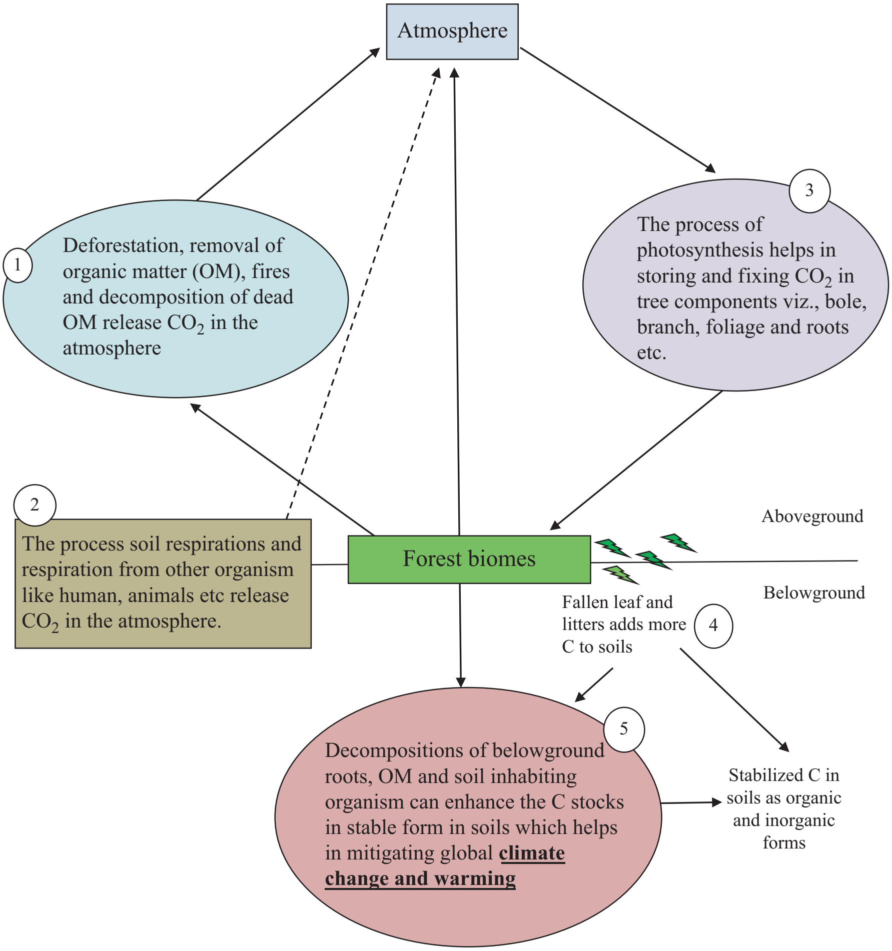

Fig. 1 Carbon flow in forest biomes and climate change mitigations. (Berndes et al. 2016)
Note: Box nos. 1 and 2 represent C stabilizations in the atmosphere, and box nos. 3, 4 and 5 show C stabilizations in both forest vegetations and soil (SOC)

under changing climate until and unless they migrate inward. Further swampy and marshy vegetation of coastal freshwater would become highly vulnerable due to salt water intrusion. Besides vegetation coral reef would be largely affected through such events (IPCC 2014).

The major impact of climate change on forests can be reflected through various events such as migration of vegetation towards higher elevation and towards pole (Ogawa-Onishi and Berry 2013; Telwala et al. 2013). Changes of biome composition, exotic plants invasion from different biomes and occupying understorey of forests are the major consequences (Singh et al. 2012). As per research reports, arctic tundra biome has reflected expansion of shrub plantation (Blok et al. 2011).

Table 1 Interaction between extreme weather or various climatic variables and tree species

Extreme weather and climatic variables	Reported tree species	Experiment conditions	Response type	References
Rising CO_2 + high temperature	Mongolian oak (*Quercus mongolica*)	Demonstrated in controlled environment, i.e. controlled chamber	+	Wang et al. (2008)
Rising CO_2 + climate-mediated low moisture stress in soil	Cork oak (*Quercus suber*)	Controlled environmental conditions	+	Faria et al. (1999)
Rising CO_2 + climate-mediated low moisture stress in soil	Red gum tree (*Eucalyptus macrorhyncha*)	Controlled environmental conditions	–	Roden and Ball (1996)
Rising CO_2 + high temperature stress	White gum tree (*Eucalyptus rossii*)	Controlled environmental conditions	–	Bassow et al. (1994)
Rising CO_2 + nutrient enrichment condition	Paper birch (*Betula papyrifera*)	Demonstrated in controlled environment, i.e. controlled chamber	Neutral	Zhang et al. (2008)
Rising CO_2 + climate-mediated drought conditions	Subabul (*Leucaena leucocephala*), a novel N-fixing tree	Demonstrated in controlled environment, i.e. controlled chamber	+	Polley et al. (2002)
Rising CO_2 + climate-mediated drought conditions	Sweet acacia tree (*Acacia farnesiana*)	Demonstrated in controlled environment, i.e. controlled chamber	+	
Rising CO_2 + climate-mediated drought conditions	Honey mesquite tree (*Prosopis glandulosa*)	Demonstrated in controlled environment, i.e. controlled chamber	+	

Note: + and – indicate positive and negative responses, respectively

Actually climate governs the structure, distribution and ecological dynamics of forest ecosystem. As a consequence of it, distribution of forest types, C emission and stocking and climate change are considered to be an integrated process. Forests can act upon climate change both positively and negatively. In a positive sense, forest is a principle tool for climate change mitigation as it acts as a global C sink. On the other hand, depletion of forest cover may cause increment in the level of atmospheric CO_2.

3 Forest and Climate Change: Global Scenario

Globally CO_2 as GHG is directly emitted through burning of fossil fuel, and other GHGs such as nitrous oxide and methane are produced through removal of forest cover and cultivation practices (Yohannes and Mebratu 2009; Meena et al. 2018). The major cause of the increasing concentration of atmospheric CO_2 includes deforestation activities under tropical climatic conditions. This therefore promotes warming of the earth's surface. Fossil fuel consumption and removal of forest cover act as two key drivers for climatic alterations causing a significant level of livelihood insecurity (Ackerman 2009).

As per the IPCC recommendation, the average temperature may increase approximately 6.5 °C at the end point of the twenty-first century (IPCC 2007). Human civilization history revealed unprecedented growth of climate change phenomenon is directly associated with GHG emission (IPCC 2013). The overall impact of such mega events includes all-round destruction of bioresources, ecological integrity and economic progress (IPCC 2014).

It has been found that the integrated system of forestry, agriculture and different land uses shares a significant amount of GHG emission. As per IPCC (2013) recommendation, it was noted that human activities contribute significantly towards GHG emission. The most probable consequences due to such events are glacier melting and atmospheric warming at the polar region, leading to the rising level of sea (IPCC 2014).

Climate change and forests have revealed miscellaneous results from global perspectives (Table 2). For example, forest plantation and natural regeneration have promoted the increase of forest cover in various countries such as China, European countries along with Latin America and Caribbean countries (FAO 2010). The effect is negative in case of tropical countries of Asian subcontinent, African subcontinent and Pacific regions along with parts of Latin America because of agriculture expansion along with continued deforestation (FAO 2009).

Globally it is a necessity to prepare a database regarding possible threats of climate change towards forest ecosystem (Millar et al. 2012). Besides forests it has been observed that water, health, genetic pool and cultivation practices come under severe threat of the climate change (Ahenkan and Boon 2010). In this context forests harmonize between maintaining integrity in the earth and ecological systems and promoting socioeconomic upliftment for forest-dwelling community. Forest also tends to combat natural hazards to a larger extent.

4 Impact of Climate Change on Forests

Climatic variation can be properly defined through various consequences such as changes in the temperature regimes, increment in the level of atmospheric CO_2, alteration in the precipitation pattern and alteration in the frequency of occurrence of extreme events. All these events have long-term impact on forest in the form of extending growth period, changes in composition of insect species and alteration in

Table 2 Climate change impacts on different tree species in various regions

Tree species	Region	Climatic effects/responsible factors	Results	References
Oak tree (*Quercus* species)	Oklahoma, USA	Severe drought under extreme climate	Declining population of oak	Rodriguez-Calcerrada et al. (2017)
Ash tree (*Fraxinus* species)	Northwestern Pennsylvania, USA	Severe drought and freezing climate, insect outbreak events	Dieback and widespread mortality	Royo and Knight (2012)
Scots pine (*Pinus sylvestris*)	Spain, southwestern Europe	Winter chilling temperature and extreme cold climate	Dieback, needle loss and large-scale mortality	Camarero et al. (2015)
Cotton tree (*Gossypium* spp.)	Southern California	Rising temperature and extreme hot climate	Emergence of pest like pink bollworm (*Pectinophora gossypiella*) causes death of the tree	Henneberry (2007)
Citrus fruits (*Citrus* spp.)	Southeastern Australia	Rising temperature and extreme hot climate	Emergence of *Epiphyas postvittana* (light brown apple moth)	Thomson et al. (2010)
Apple pear (*Pyrus pyrifolia*)	Rajgarh, Himachal Pradesh, India	Rising temperature as global warming	Diversion of species in area as from apple to peach	Anonymous (2008)
Apple tree (*Malus pumila*)	–	Rising temperature as global warming	Affect reproductive biology as lowering in the fruit bud formation and small flower	Chadha and Awasthi (2005)
	Kullu and Shimla districts of Himachal Pradesh, India	Change in temperature	Diversion of species in area as from apple to kiwi	Gulati (2009)
Sal (*Shorea robusta*) and Gurjan (*Dipterocarpus turbinatus*)	Southeast Asia	Climate change and deforestation	Threatened and loss of species	Deb et al. (2017)
Mangosteen (*Garcinia indica*)	Northern Western Ghats, India	Wide temperature variation under changing climate	Threatened and decline in suitable distribution of species in Western Ghats	Pramanika et al. (2018)

the frequency of forest burning. Prevalence and outburst of pests are secondary problems which are aggravated through climate change. As per IPCC report (2007), 33% of global diversity of species are facing the fate of depletion through climatic perturbations, as reflected from mountain and tropical ecosystems.

Global warming has imposed its positive impact through higher growth of trees with prolonged duration of growth (Lucier et al. 2009). Such facts reflected positive correlation with high temperature regime and elevated CO_2 level. Negative impacts include shifting of vegetation, changes in successional pattern, abiotic stress in terms of drought and heat stress for forests plants leading to high mortality globally (Allen et al. 2010). All these consequences are the outcome of intense change in climatic conditions. Humans are just aggravating the problems in the form of releasing ozone-depleting substance, emission of nitrous oxide, spread of insect species, fragmentation of habitat and forest fire (Bernier and Schone 2009). The rising level of sea due to warming of the earth's surface is engulfing tidal freshwater as well as marine forest to a considerable extent (Di Nitto et al. 2014).

As per the records, future prediction of climate change will tend to have different dimensions of ecological impact. The major impact includes widening or narrowing of species ecological amplitude, shifting of ecological zones and alteration of forest productivity (Campbell et al. 2009). Depending upon the forest type and vegetation structure, it has been found that forest ecosystem such as boreal forests, mangrove forests, alpine biome, tropical deciduous forests and forests under Mediterranean climate is severely affected due to climate change (Bernier and Schone 2009; Huntingford et al. 2013; Datta et al. 2017) (Fig. 2).

4.1 Climate Change and Vegetation Growth Trait

Alteration in the climatic elements imposes its impact on energy flow, nutrient cycling, productivity, diversity, ecological process and C balance of forests. Time is also a very important factor from physico-chemical and biological perspectives (D'Aprile et al. 2015). Amplification of the negative impacts may be a serious consequence for managing forests in a sustainable way under climate change. Climatic elements tend to influence the growth of forest in a significant way in the form of increasing and decreasing pattern in the growth periods (Merian et al. 2013). Climatic perturbation through rainfall and temperature regimes is a key factor that regulates growth of trees (Sedmak and Scheer 2015). Under traditional system of forestry, emphasis is being given on yield attributes such as wood content, log volume and regeneration capacity which do not often consider the climatic irregularities, affecting tree growth as well as pattern of growth on time scale. Such type of approaches is unable to predict the optimum growth period for forest trees and factors responsible for that. It has been found that silvicultural and harvesting practices promote the emission of C based on temporal variability.

Time management could be an effective tool in order to promote forests to mitigate and adapt to climate change under changing scenario (Lafortezza et al. 2013). Two crucial factors that regulate the energy balance on the earth and universe

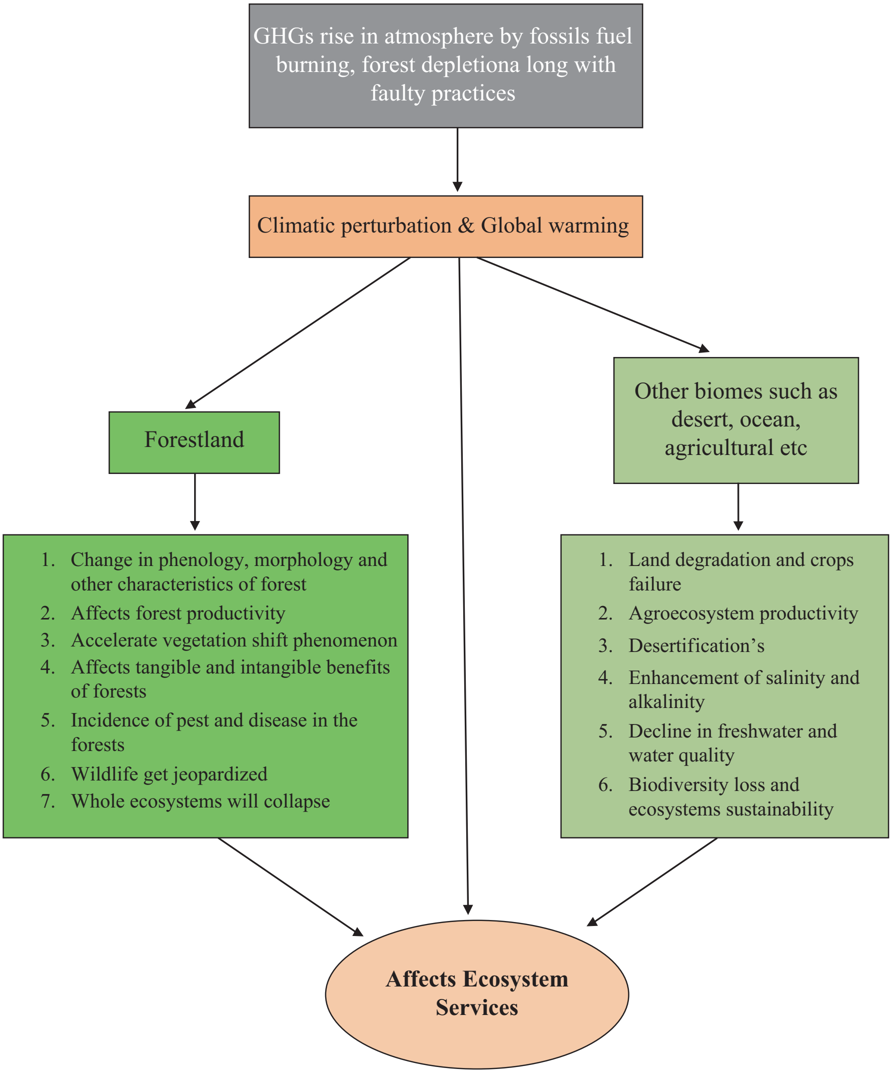

Fig. 2 Forests and other biomes under changing climate. (Berndes et al. 2016; Singh et al. 2012; Campbell 2009; Bernier and Schone 2009)

include the diversity of organisms and climate. Biodiversity is a consequence between changes at the molecular level along with changes in the evolutionary perspective leading to maintain the equilibrium between the earth and outer space. The key issues of the present decade include the increase in the ambient CO_2 level. The most obvious consequences of it include global warming and alteration in C cycle.

The impact of climatic variability has a strong influence over forest growth at local level (D'Aprile et al. 2015). Growth responses vary according to climatic perturbations (Pretzsch et al. 2014). The interaction between climatic changes and growth of forest can be used as a strategy for SFM.

4.2 Climate Change and Vegetation Productive Trait

Productivity of a forest ecosystem depends upon the temperature, precipitation and availability of nutrients. However the response of forest trees may vary on the basis of their adjustment to changing climatic conditions (Das 2004; Jhariya 2014). Alteration in the temperature regimes affects the key processes of forest ecosystem which include nutrient cycling, litter decomposition and root dynamics for nutrient uptake along with other associated dynamics of forest ecosystem (Norby et al. 2007). Increase in the temperature may be advantageous for vegetation during colder periods and may be disadvantageous during dry season (Garrett et al. 2006). Under increasing temperature condition, moisture level in the forest would be severely affected due to alteration in the temperature and precipitation pattern. Higher temperature tends to promote evaporative process and evapotranspiration process which tends to reduce the water use efficiency of vegetation and alters the salt water balance within the plant system leading to poor growth and development (Mortsch 2006).

Extended period of warmer season may promote moisture stress and drought condition which may impact on growth of forest trees depending upon the vegetation characteristics as well as the nature of the soil (Mortsch 2006). It has been found that young stands of vegetation in the form of saplings and seedlings are much more vulnerable towards climatic changes than mature trees due to the storage of metabolite at higher level.

Plants with shallow root growth under shallow substratum would be severely affected by the moisture deficit. On the other hand, plants with deep fibrous root are not that much vulnerable in terms of growth due to water stress. Research reports reveal stress factors such as moisture and drought increase the vulnerability of vegetation towards pest outbreaks and diseases. Even they may become more susceptible towards events such as forest fire. Hogg et al. (2008) reported the reduction in productivity and death of *Populus tremuloides* (quaking aspen) species found in the western part of Canada. Negative impacts include defoliation and boring of woods by pathogenic organisms. Drought has induced stand replacement and growth retardation in case of *Fagus sylvatica* (European beech) in Spain and other parts of Europe (Jump et al. 2006).

Ambient level of CO_2 promotes growth and water use efficiency in vegetation in the absence of other limiting factors such as nutrient and water. Such event takes place up to a certain limit beyond which the positive impact may turn towards negativity (Stone et al. 2006). Morphological changes can take place under elevated level of CO_2. Changes include increment in the number of leaves, leaf area, more thickness of tree girth and branches, etc. (Garrett et al. 2006). It has been found that changes in floral structure and forest dynamicity are based upon the nature of species and its associated environmental conditions in response to increased CO_2 level

(Bauer et al. 2006; Varma et al. 2017). Research reports reveal higher ground-level concentration of ozone may increase the vulnerability towards pathogen and lesser productivity (Karnosky et al. 2005). Another finding includes increment of growth and productivity for boreal forest at higher level of nitrous oxide (Stone et al. 2006).

The productivity of a forest ecosystem is a very important parameter for growth and development. It has been observed the productivity rate varied significantly depending upon geographical area, species composition, age, structure of forests, lithology, CO_2 concentration and nutrient availability (LeBauer and Treseder 2008). Under climate change scenario, water stress reduces plant growth, and under surplus conditions, the growth may be ceased as revealed for CO_2 and N (LeBauer and Treseder 2008; Ollinger et al. 2008). The productivity rate of forests increases as the temperature increases which may be due to the higher presence of CO_2 (Fig. 3). The condition is a little bit different under tropical condition where changes take place seasonally, and productivity rate may decrease after C saturations (Feeley et al. 2007). Water scarcity may also act as another factor to cause decline in productivity (Malhi et al. 2008).

Overall the climate change has multidimensional impact (Table 3) over the forest ecosystem through alteration in the species composition, productivity rate, growth rate, growth and yield attributes and also the site physical characteristics (Williamson et al. 2009). Further increase in the temperature may promote forest productivity up to a limit and then show further decline (Fischlin et al. 2007). The seasonal pattern of climatic change may impose a bigger impact over forest ecosystem than an annual impact on a long-term basis (Bugmann and Pfister 2000).

4.3 Climate Change and Vegetation Shift Scenario

Climatic variation is a mega event in terms of changes in species composition within forest ecosystem. On a long-term basis, climatic variation has severe consequences over forest species composition. Depending upon the climatic pattern of an area, there are shifting paradigms from one vegetation type to another just like ecological succession process. Species distribution changes take place on latitudinal and altitudinal extremes under the influences of changing climate. Research reports reveal shifting forest vegetation towards higher altitudinal area in response to global warming (Menendez 2007). Lenoir et al. (2008) reported long-term study of altitudinal distribution of forest vegetation which revealed a paradigm shift towards upward direction at the rate of 29 meter per decade. Climate change alters spatial pattern in relation to forest flora (Lenoir et al. 2008).

Among the vegetation types, short-day plants were found to relocate in the form of altitudinal shift, whereas long-day plants such as hard woody species reflected lesser impact of climate change. Such changing pattern would alter the entire configuration of forest ecosystem. Climatic extremes such as drought-induced stress in oak species have been reported in Spain, Portugal and Italy and their subsequent dieback (Resco de Dios et al. 2007). Research findings reveal migration of forest species at higher altitude and even extinction of species (DoEST 2012). Research

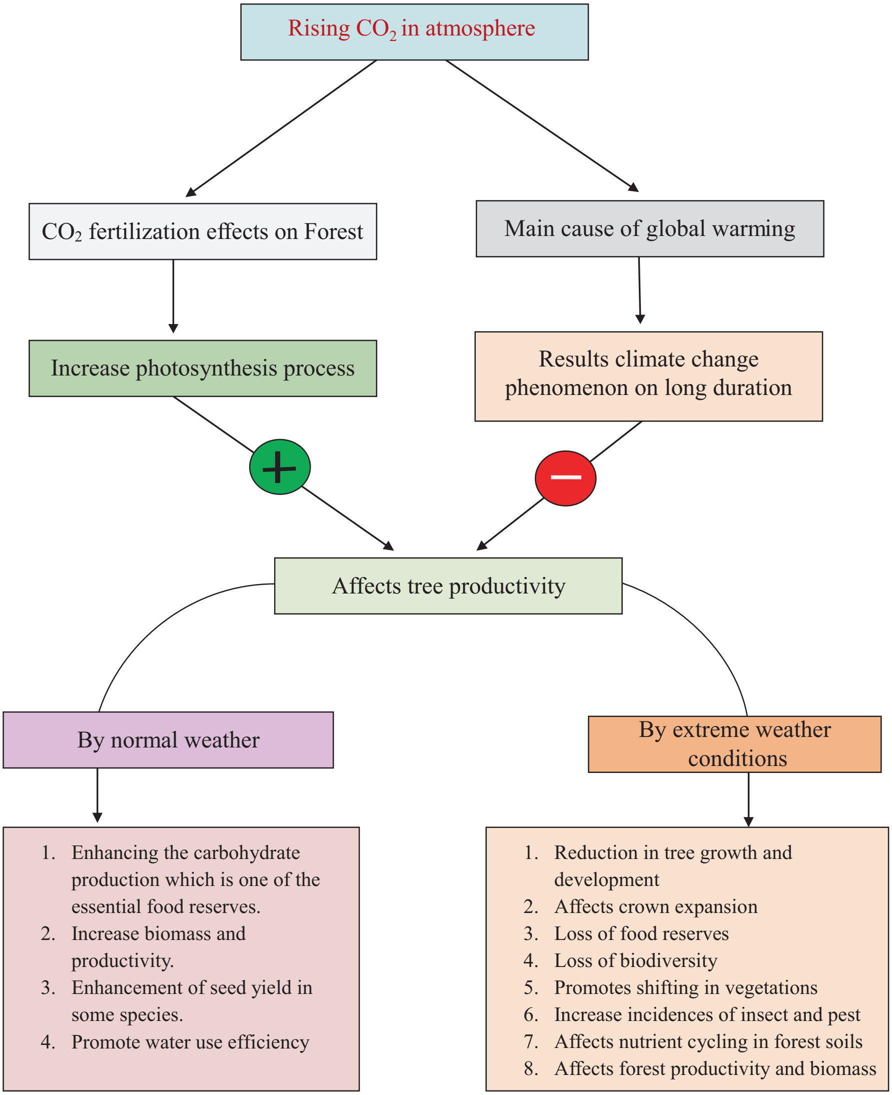

Fig. 3 Rising CO_2 and tree productivity. (Ramirez and Kallarackal 2015)

reports reflect *Pinus longifolia* (pine), *Aconitum heterophyllum* (Indian Atees), *Woodfordia fructicosa* (Dhawai) and white Himalayan lily (*Lilium polyphyllum*) showed upward migration at higher altitude within a century (DoEST 2012). In economic sector orchard plantation has also reflected such shifting in terms of lower economy output causing problems for livelihood. Interesting studies reflect species invasion or species replacement of *Quercus leucotrichophora* (Banjh oak) to *Pinus roxburghii* (chir pine). Further it has been observed species such as shisham

Table 3 Elevated CO_2 impacts on biomass, productivity and other vegetative growth varying forest in world

Tree species	Environmental factors	Responses	References
Mixture of three species, viz. *Fagus sylvatica* (common/European beech), *Betula pendula* (silver birch) and *Alnus glutinosa* (black alder)	Elevated CO_2	Enhancement in above ground biomass from 15.2 ± 0.6 to 20.2 ± 0.6 kilogram per m^2, i.e. 17% increment	Smith et al. (2013)
Tree species like silver birch (*Betula pendula*)	Elevated CO_2	Leaf area index (LAI) was increased by 37%	
Tree stand of loblolly pine (*Pinus taeda*) and sweetgum (*Liquidambar styraciflua*)	Elevated CO_2 of 550 part per million	Enhancement of net primary productivity by 23 ± 2%	Norby et al. (2005)
Populus tremuloides (aspen), *Acer* species (maple) and *Betula pendula* (birch)	Elevated CO_2	Enhancement in leaf area index value	Oksanen et al. (2001)
Black poplar tree (*Populus nigra*)	Elevated CO_2	Productivity enhanced by 225%	Gielen et al. (2001)
Some conifers tree species	CO_2-enriched, i.e. elevated CO_2	Positive impact on biomass as enhanced by 130%	Saxe et al. (1998)
Loblolly pine (*Pinus taeda*)	Raised CO_2 level	91% increased seed weight	Hussain et al. (2001)
Natural stand of oak tree-based forest in Florida comprised *Quercus myrtifolia* (myrtle oak), *Quercus geminate* (sand live oak) and *Quercus chapmanii* (Chapman oak)	Elevated CO_2	Significant effects on acorns resulted in higher production	Stiling et al. (2004)
–	Elevated CO_2	Enhancement in root-to-shoot mass ratio	Oechel and Strain (1985)
Tulip poplar (*Liriodendron tulipifera*)	Elevated CO_2	Neutral effects on root-shoot ratio	Norby et al. (1992)
Tree species like white poplar (*Populus alba*), cottonwood poplar (*Populus nigra*) and Canadian poplar (*Populus euramericana*)	Elevated CO_2	Affects belowground production as enhancement in belowground biomass up to 76%	Lukac et al. (2003)
–	Elevated CO_2 of 550 part per million	Fine roots biomass increased by double figure	Norby et al. (2004)
Oak tree stand comprised *Quercus petraea* (sessile oak) and *Quercus robur* (common oak) of Northeastern France	Elevated CO_2	Basal area increment	Becker et al. (1994)
Tropical forests	Elevated CO_2 of 550 part per million	Significantly increased NPP by 35%	Collatz et al. (1991)
Temperate forests	Elevated CO_2 of 370 part per million	Significantly increased NPP by 26%	

(*Dalbergia sissoo*) and deodar (*Cedrus deodara*) revealed population decline due to the influence of climate and human (DoEST 2012).

Parmesan (2006) reported the migration of alpine vegetation beyond their distribution range. Vegetation shift has also taken place in Siberia, Canada and New Zealand, and northward migration has been reflected in the eastern part of Canada and Sweden. Montane rainforest under tropics reflects shifting paradigm to higher altitude (Jones et al. 2008). Such shifting paradigm may not only regulate by temperature but also by seed dispersal ability into newer regions which poses suitable climatic elements with anthropogenic influences for species dispersal and alteration in the disturbance regimes (Monserud et al. 2008).

Alteration in the quality of ecosystem has imposed significant change in forest ecosystem. Ecosystem change includes alteration in the rainfall pattern, abnormality in dry and wet period and alteration in characteristics of soil with subsequent change in the sea level. Such events steal out the adaptability of forests species under changing environment. It has been observed that regeneration potential, age structure, species diversity and forest dynamics significantly alter (CCFM 2009). The age structure of forest reveals that seedlings and older plantation are much more vulnerable towards climate change than younger ones. In the era of climate change, forest vegetation reflects three modes of responses. Firstly, on the basis of their ecological niches, forest trees migrate spatially. Secondly, wider adaptability in their habitat range in forestland. Thirdly, the worse situation includes the total extinction of species (Aitken et al. 2008). To predict the ultimate fate of forest tree species, one needs detail knowledge at the genetic level to community level with ecological functioning on spatial basis. Time-bound analysis includes proper knowledge regarding growth cycle and traits of forest vegetation.

Jorgenson et al. (2001) reported that degradation of permafrost in Alaska has caused vegetation shifting into bogs and fens from birch forests. Global warming-induced depletion of permafrost has led to conversion of densely populated bogs to non-populated fens in western Canada (Vitt et al. 2000). Climatic perturbations even show their negative impact on *Chamaecyparis nootkatensis* (Alaska yellow cedar) type of hardy species in the bane of extinction as high as up to two lakhs hectare geographical range (Hennon et al. 2008).

4.4 Climate Change: C Dynamics and Forest Soil

Interrelationship between C assimilation and climate change scenario has the biggest implications for sustainability of forest ecosystem. More concentration of CO_2 assimilates in vegetation, the more will be the reduction in ambient CO_2 level, and as a consequence, the global warming phenomenon can be checked. Such mechanism has been widely adopted by the tropical countries to participate in the C trading process. Simultaneously the increase in the C stock and reduction in ambient CO_2 level take place. Economic policy designing in the sustainable management of forests has already being initiated at tropical conditions as well as other foreign countries (Sanchez Chavez 2009).

Under the event of climate change, possible inevitable facts include rising temperature and long dry spell of climate with gradual increment of ambient CO_2 concentration which significantly reduces C storage potential of forests and converts them as a source of CO_2 emission (Ollinger et al. 2008; Nepstad et al. 2008; Yadav et al. 2017a). C sequestration and productivity are intricately interrelated with each other. Normally increasing temperature leads to lesser C storage on short time span basis. However the situation may be changed in case of temperate climatic conditions.

Climate change has serious consequences in relation to nutrient dynamics, soil C level and soil moisture level. It has been revealed that C storage in soil makes them a large potential source of GHG emission. Climate change imposes significant impact on soil resources by various ways. Bradley et al. (2005) reported various modes of depletion of soil resources due to climate change. Temperature increase would increase the rate of soil respiration leading to depletion of soil C. Further dry spell due to lack of rainfall stimulates evapotranspiration at a higher rate which further causes loss of soil C. Alternatively it was observed the higher level of tree productivity due to higher litterfall on forest floor is a consequence of increment in ambient CO_2 level.

Further warm temperature may produce higher temperature in soil surface due to higher rate of soil respiration which may enhance soil C level. Higher growth rate of trees may also prove to be negative in terms of depletion of nutrient, soil acidification and reduction in productivity level at the long term. Alteration in soil C and nitrogen (N) level significantly influences C/N ratio which may create problem for understory vegetation of forestland. Climatic extremes in terms of heavy rainfall promote higher soil erosion. High temperature along with heavy rainfall may cause depletion of dissolved organic carbon (OC) of forest soils. Bradley et al. (2005) mentioned interrelationship of mycorrhizal species, ground vegetation and host plants is determined by the level of atmospheric CO_2, pollution and moisture content of soil.

Considering changing climatic scenario SFM is the need of the hour. Adaptive strategies and mitigation policies need to be formulated and implemented at the grassroot level. In this connection plantation of leguminous trees would be a fruitful option for nutrient building of forest floor. Leguminous species through biological N fixation mechanism improves the N content of the soil. Further they also promote growth of soil microbial biota (Banerjee et al. 2018; Jhariya et al. 2018; Ashoka et al. 2017). To restore soil quality under the era of climate change, biological processes are the most suitable answer. In this path plantation of fast-growing species giving higher biomass input is another suitable technique which may improve the soil C stock. Climate change often produces climatic extremes such as heavy rainfall which may erode the top soil completely. Proper forest cover may help to combat such problem and help to conserve soil resource (Jhariya et al. 2018; Banerjee et al. 2018).

5 Forest: Climate Adaptation and Mitigation

Combating changing climate involves both adaptive and mitigatory measures. Globally a harmonized approach is required between mitigatory and adaptability towards changing climate (IPCC 2002). IPCC has addressed this particular issue from biodiversity conservation perspective. Adaptation includes responses of biota towards climatic perturbations in order to reduce hazards and negative consequences and generate more beneficial opportunities. Three modes of adaptation have been recognized from climate change perspectives such as adaptation in perception of climate change, people's participation and towards scientific and systematic adaptation approaches (IPCC 2002). The site of adaptation may extend up to the individual basis starting from ecosystem, community and population. Adaptation has both long- and short-term outputs. On long-term basis, the impact would reduce GHG emission reduction, and short-term consequences include the benefits to the implementing countries.

Climate change mitigation is recognized as a major issue worldwide from the climate convention and Kyoto Protocol discussions. UNFCCC aim towards GHG emission reduction, facilitate the negative consequence reduction towards human civilization in relation to climatic variables. Alone mitigation cannot supersede the changing climate. Climate change is a phenomenon which obviously has negative consequences either on a short-term or long-term basis. Therefore, mitigation should be accompanied by adaptation strategies (Bruce et al. 1996).

Forest vegetation tends to combat the changing climate under increasing C pool within soil-plant system and also provides a secondary path for generation of fossil fuel energy. Species also promote C in different plant components. SFM is an integrated approach in the area of climate change mitigation which aims towards more biomass production and therefore increase in the C stock (Fig. 4). There is a significant variation in C storage capacity in various regions of the world. The time frame for mitigating climate change is a crucial factor. Young vegetation stand has higher C sequestering potential than the old and degenerating stand. Also in mature stand, the C sequestration reaches saturation limit. Therefore, mitigation of climate change can be mediated through growing stock of population. On time frame increase in the forest cover through afforestation process leads to further C sequestration and climate change mitigation.

Three broader approaches were considered during climate change mitigation strategies. It includes management of C stock and conservation, increase in the area of C sink and exploring suitable alternatives for fossil fuel (Brown et al. 1996). C emission reduction with inhibition of deforestation is the primary countermeasure towards climate change. Secondly, reforestation practices in the degraded land to trap atmospheric CO_2 are another feasible measure towards climate mitigation. Mitigation strategies vary depending upon the land-use pattern, soil quality and policies of landholding which is interrelated towards using forest for resource purpose with socioeconomic development.

Optimum strategy development often leads to contradiction in the form of timber harvesting under the aim of increasing C stock. Apart from these, natural disasters

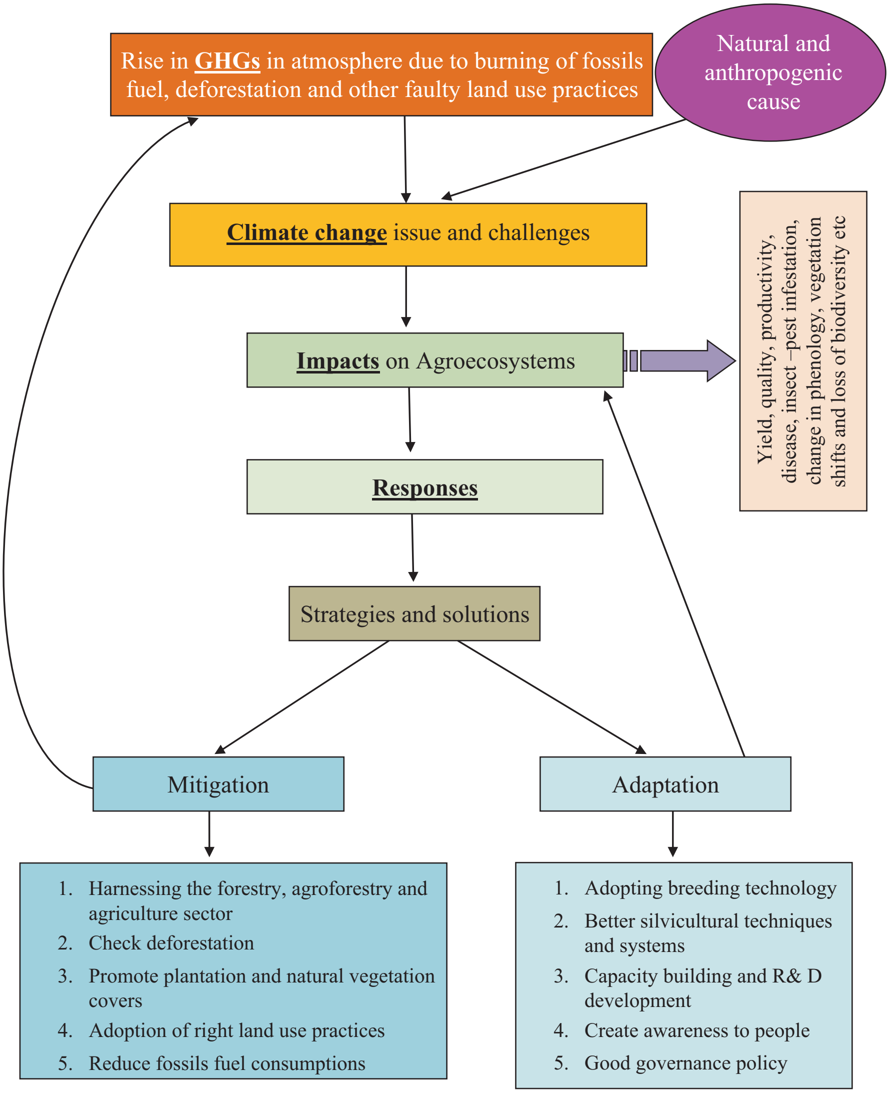

Fig. 4 Climate mitigation and adaptation through forestry. (Patosaari 2007; Keenan 2015)

also influence the C stock of forests. Some sustainable strategies need to be reoriented at the national and regional level to promote mitigatory measures towards climate change. This important agenda includes reducing deforestation, improving productivity of forests, checking peatland drainage, reducing damage to forests by storm, reducing the impact of natural calamities and reducing wood consumption through finding suitable energy alternatives. Development in the rural sectors should be harmonized with mitigatory measures for climate change. It has been reported that wood has low C footprint due to their higher efficiency of C utilization during their production and processing steps. Wood is highly efficient in this matter as it can be used as bioenergy even after the product life. It should be incorporated at national policies to promote the alternative use of wood in order to combat climate change.

From global perspectives, the adaptation strategies need to be varied in order to promote sustainable adaptation depending upon the conditions of the local environment. This is true for the forest of Europe. Overall the necessary adaptation measures need to be designed for each specific region. The target sectors include regeneration of forest, stand tending and thinning, sustainable harvesting, planning at the forest management level, forest protection measures and silvicultural schemes, good communication and infrastructure development, nursery and breeding of trees and overall suitable forest policy.

The major hindrances in this process include major uncertainty of the climate change phenomenon, lack of proper adaptation strategies for most countries, a huge gap in the field of vulnerability assessment and work at the grassroot level. Lack of adequate training of the individuals involved in such task and funding resources and last but not the least public awareness regarding these issues, which is the biggest challenge.

From the perspective of adaptation towards climate change, it has been found that limited approaches have been addressed towards studying the local impact of climate change due to its uncertainty. Therefore, there is an urgent need to formulate experiment and execute suitable adaptation policies. In this connection, ecosystem resilience is a suitable approach as it is the inherent capability of ecosystem to prevent change and alteration. Strategies should be integrated between biodiversity maintenance and social values along with economic output (Raj et al. 2018b). Studies regarding adaptation option under variable level of disturbances need to be further researched.

6 Key Issues and Challenges for Forests Towards Climate Adaptation

Disturbances in the forest ecosystem are influenced by the climate of a region. For example, species outbreak in the form of ecological invasion, problems of pest and disease infestation and occurrence of natural calamities such as drought, fire, landslide, etc. can alter the structure, function and dynamics of forests (Dale et al. 2001; Jhariya and Yadav 2017; Meena et al. 2015). The susceptibility of forests towards disturbances may change depending upon the climatic conditions through increase forest fire, frequent occurrence of natural calamities and other such perturbations (Mortsch 2006).

Reports of Gopalakrishnan et al. (2011) reveal nearly half of India’s forests areas are very much susceptible towards climate change. Areas include Eastern Ghats, upper Himalaya, north of Western Ghats and central part of India. Such findings are further supported by Chaturvedi et al. (2010) who report the changes in forest types can take into account up to 77%. Such types of impact overall are highly deleterious for forest ecosystem due to the integrated system of forest, disturbance regimes and climatic elements. These factors can increase the severity of the others in terms of structural change and degradation of forest area. For example, it has been observed that forest infested with pine bark beetles becomes highly susceptible to natural calamities such as the Hurricane Mitch in 1998. The infestation of these beetles promotes higher mortality in tree which simultaneously increases fuel loads and then risk of wildfire.

All these impact have wider dimension over the forests. Whatever may be the impact through ecological events and natural calamities, the mostly influenced part includes forest economy (FAO 2005). The total forest economy would change due to higher competitiveness as well as changes in the forest structure and composition due to climate change. Improved social and environmental vulnerability includes changes in ecosystem services, conservation services, risk in livelihood security and other sociocultural problems.

The IPCC (2002) reports harmony between mitigation and adaptation of climate change involving negative consequences of changing climate, exploring possible solution towards mitigation of climate change. While going for mitigation and adaptation towards climate change, one needs to consider some of the key important facts. Firstly, one needs to look for the hazardous impact of mitigatory strategies that may put forest ecosystem into vulnerable condition. Secondly, different strategies can be incorporated in the policy matter of mitigation aiming towards reduction in vulnerability. It has been found that projects also contribute towards vulnerability reductions, conservation of biodiversity, habitat protection and sustainable management of forests. Adaptation strategies such as urban forestry, climate-resilient practices and conservation approaches contribute significantly towards mitigating climate change. Proper harmonization within adaptive and mitigatory measures that reduce the negative cost caused by the changing climate and provide secondary benefits needs to be designed. The problem of forest degradation is further aggravated through population explosion, pasturing activity and many other factors. Such problems should be minimized at the grassroot level to achieve sustainability.

Some of the major challenges associated with adaptation and mitigation of climate change include the following:

- The complex nature of tropical forests
- Different land-use patterns and prevailing landholding policies
- Reducing economic viability considering ecological standpoint
- Decline in the production of tropical forests
- Legal enforcement and protection
- Efficient functioning of the global degradation process such as deforestation, loss of biodiversity, etc.
- Malfunctioning of the administrative machinery of the forest sector
- Rural poverty
- Jeopardize of forests in the name of development
- Lack of adequate database
- Improper political will

Lack of funding
Knowledge gap regarding functional role of forests towards mitigation of climate change
Shortage of staff
The corruption prevailing in the forestry sectors

In the present context, the view of adaptation towards climate change includes finding out the advantage of benefits that occurs due to change (Levina and Tirpak 2006). In the present context, the underlined principles of SFM address that the issue of climate change needs to be understood. In most of the cases around the world, proper implementation of SFM strategies often limits the climate change adaptation process (Innes et al. 2009). Management of forest department needs to integrate approaches on spatial and temporal scale to address the future risks. Key climate change mitigation strategies at the present era include more utilization of wood as bioenergy and incorporation of wood as a material for construction activities and industries. The changing scenario of urbanization is putting pressure on rural people to reduce their capacity in labour work aiming towards forest management (Ince et al. 2011).

7 Sustainable Forestry Practices and Climate Change

Combating the changing climate is the biggest issue in the entire world at the present century. One simple way to do so includes implementation of proper sustainable forestry practices. By the term sustainable forestry, we mean specific ecofriendly approaches to increase forest cover through reforestation, afforestation, agroforestry practices and improved silvicultural schemes. Such approaches increase the C sink of the world. Another focus should be given on converging degraded wastelands into forested land. Proper land-use practices in the form of agroforestry, farm forestry, extension forestry and social forestry may further promote or increase the area of C sink, thus also helping to reduce the ambient CO_2 concentration in the atmosphere (Jhariya et al. 2015; Singh and Jhariya 2016; Verma et al. 2015).

Results revealed that wood from sustainable management of forest in European Union revealed lower C footprint in their entire lifetime (0.9 t of CO_2 per cubic meter). Wood products can be efficiently recycled which gives suitable substitution for fossil fuels. This therefore causes reduction in the level of C (2.1 tons) due to lesser energy requirement for various activities. Policies related to forestry and alteration in land utilization and land-use pattern can negatively impact biodiversity and increase the risk on forests. Very interestingly climate change adaptation promotes all-round sustainable development in the form of biodiversity conservation and improvements in the C reserve (IPCC 2002).

Under traditional forest management system, activities such as cutting, thinning and harvesting may become unsuitable affecting the growth of forest tree species. It has been observed that the decrease in the growth of tree species within a vegetation stand may lead to lowering of C storage. Further higher CO_2 emission by consuming higher amount of wood mass shows negative reflection in terms of reduction in CO_2 storage potential as biomass of the forests (D'Aprile et al. 2015).

Climatic elements need to be considered in relation to harvesting of mature crops under forest ecosystem which may lead to positive trend in growth. In order to perform such activities, one needs to explore the climatic variables up to 15 years. For future perspective, climatic variable needs to be thoroughly studied to screen out the threshold value showing positive growth response for the species, type of forests and overall ecological region. Also from vegetation standpoint, attributes such as productivity, growth, biodiversity as well as C balance with respect to climatic variables at the concerned site level need to be explored (D'Aprile et al. 2015).

Holistic approach between mitigation and adaptation towards changing climate focuses on alteration in land utilization or technological development (Fig. 5). Verchot et al. (2007) mentioned that agroforestry is a fruitful option which provides both mitigatory and adaptive approach towards climate change. There are several benefits of agroforestry practices which include reduction of soil erosion, improving ecosystem resilience against natural calamities, improving soil fertility through increased OC content, reduction in crop failure mechanism and overall sustenance of biodiversity as was seen in Indonesia (Clough et al. 2011). Alternative strategy towards adaptation aims toward increasing biomass and soil organic matter (OM) content by reforestation practices, as well as the protection of ecosystem contributes significantly towards climate mitigation through sequestration of C. One interesting fact is that mono-cultivation of exotic species may promote higher C flux from the atmosphere to plant than indigenous species but simultaneously reduce the ecological functioning and biodiversity status of forests. However, this can be compromised for the sake of the C storage (Diaz et al. 2009). Under tropical condition, reforestation promotes better climate mitigation and adaptation (Sasaki et al. 2011).

Anderson-Teixeira et al. (2012) reported about the variable scenario in the high altitude as reforestation promotes warming conditions due to reduction in the albedo values. Qin et al. (2011) mentioned that energy crop plantation in the degraded or barren land has a huge potential for reduction of C emission, but it has some negative consequences in the form of conversion of C-rich ecosystem into cropland. The mechanism including reducing emissions from deforestation and forest degradation (REDD+) can reduce the potential risk of negative consequences of C emission, and therefore economic incentive structure needs to be formulated specifically (Busch et al. 2012).

Management of forest emphasizes towards livelihood generation and poverty alleviation (Larson 2011). Right over resources is a very essential thing towards promoting livelihood benefits for local community stakeholders (Macchi et al. 2008). REDD+ have been implemented focusing recognition of forest rights (Angelsen 2009). Strategic suggestions reveal that community stakeholders can bridge between climate change and biodiversity conservation (Salick and Ross 2009). It deviates from adaptation towards ecosystem as forests are being considered to be utilized as resource by the local community (Campbell 2009). However REDD+ can act effectively in timber production by the consequence of low logging activity (Putz et al. 2012). Integrated approaches such as ownership of forest

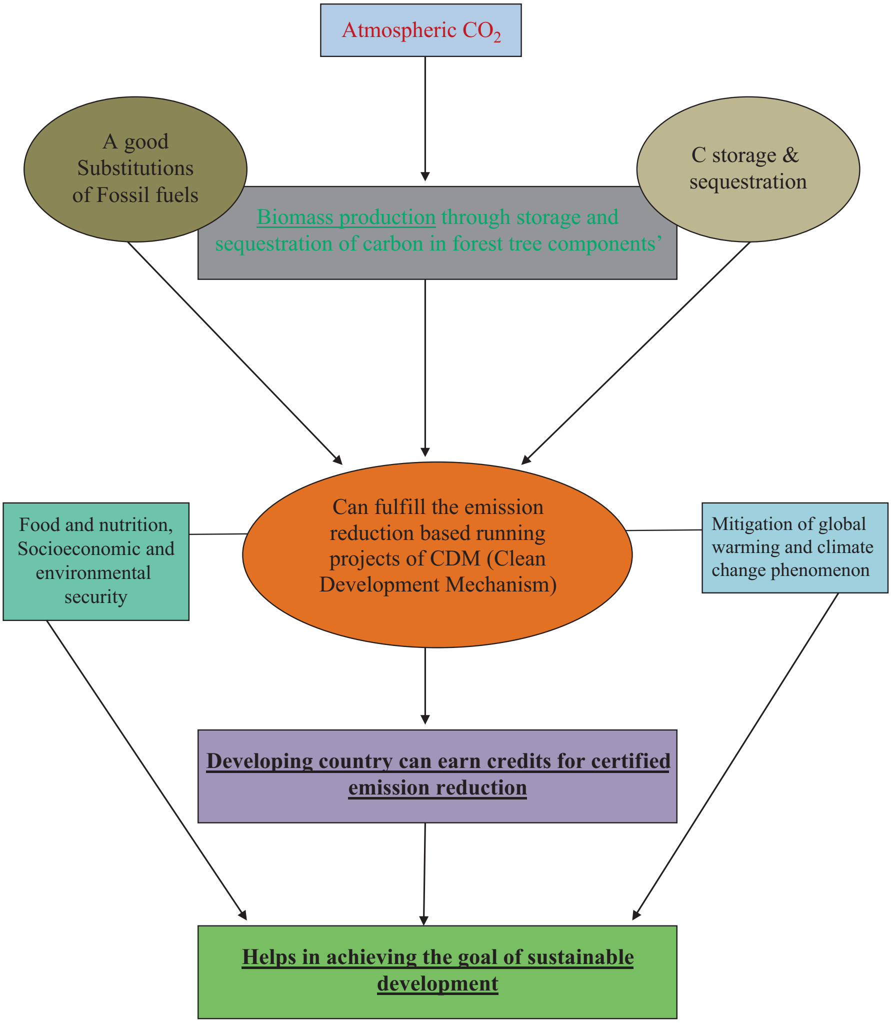

Fig. 5 Mitigating climate change and sustainable development. (FAO 2016; UN 2015, 2017; IPCC 2002; Keenan 2015; Millar et al. 2012)

products, sustainable harvesting and management and community empowerment may be the fruitful strategies (Putz et al. 2012). As per reports the higher rate of C sequestration in organically rich mangrove soil and soil of peat swamp wetland forest ecosystem may work efficiently in adaptation and mitigation by restoring degraded areas (Page et al. 2011; Donato et al. 2011).

Agriculture, forestry and other land use (AFOLU) imposes a significant role towards food crisis aiming towards sustainability. Through biogeochemical cycling of nutrients, plants uptake CO_2 from the atmosphere and N from soil and return back as biomass (below+above ground) litter and OM present in the soil. Major

GHGs such as CO_2, methane and nitrous oxide are frequently released through plant respiration, through decomposition of dead OM and through ignition. Biotic disturbances such as alternate land-use activities in the form of forestland conversion into agricultural area and grassland to pasture land further aggravate the problems of GHG emission.

A modification under AFOLU scheme includes changes or alterations in atmospheric emission of GHGs and contributing more in the soil and vegetation in the form of C stock. Alternate land-use practices in the form of agroforestry may reduce atmospheric CO_2 level and provide a suitable alternate in the form of biological products in place of fossil fuels. However, some strategies are available to combat such event of climate change in the form of changing lifestyle, preventing food wastage, altering the consumeric nature and lesser dependency towards forests from wood consumption perspectives. From the ancient time, it was observed that AFOLU played a significant role for food, fodder and fibre production globally. It also provides various ecosystem services and environmental goods for human prosperity (MEA 2005). GHG emission is a little bit lower for non-CO_2 gases due to the limited level of sources such as forest fire and wetland degradation due to water abstraction. As per the records, forestry and other land uses (FOLU) act as sources for CO_2 emission up to 33% for two centuries and up to 12% within the 9-year span of the last decade (Pan et al. 2011). The use of excessive chemical fertilizers in the modern agricultural system also contributes significantly towards climate change (Le Quere et al. 2013). As per research results, it was observed that FOLU CO_2 emission was reduced due to lowering of deforestation (FAOSTAT 2013).

8 SFM for Biodiversity Conservation and Livelihood Management in the Tropics

Forests play various beneficial roles for prosperity and growth of human civilization. It maintains hydrology, regulates hazards from natural calamities, provides economic benefits and works for social well-being (FAO 2006). Forests are the backbone of biodiversity at the global scale and also provide livelihood for more than one billion people.

SFM is an integrated approach that integrates environmental stewardship by maintaining ecological integrity through biodiversity conservation and productivity. It also takes into consideration about the various functions at various levels having impact over the global ecosystems. Climate change is such an event which does not have any single solution, and therefore multidimensional strategies are required to combat such problem. In this direction predicting climate change is a suitable option. The major focus in SFM should be addressed towards the management strategies and their influence to C cycle under the changing climate scenario and subsequently how it impacts the global biodiversity.

Forests has multifunctional role in terms of economic returns. The main output of forest in terms of economic return is wood. Apart from this forest often provides various types of non-timber forest products (NTFPs) which invariably promote livelihood security and social well-being of community stakeholders (Painkra et al. 2016). NTFPs play a significant role in the secondary sector such as fulfilling daily needs of forests dwellers, off-farm outputs and a source of income during lean period (Osman-Elasha et al. 2009). The problem of climate change would significantly affect NTFP production which in turn will impact those people who are poor and resource dependent below the poverty line and use NTFPs as income source. Such events take place under climatic irregularities and natural disturbances present in forests. Future exploration is required considering the theme of climate change and their impact over NTFPs and its socioeconomic services. Activities having economic orientation such as mountaineering and skiing in low altitude would be influenced by temperature increase. Osman-Elasha et al. (2009) reported that proper database of influences of changing climate upon recreational services needs further explorations. Very few works have been reported on this particular issue, and those which have been reported are focused at the local level. It has been reported that climate change significantly influences the forest biodiversity in Africa (Osman-Elasha et al. 2009).

Climate change jeopardizes forest ecology and socioeconomic dimension of forest ecosystem. The ecological consequence of NTFPs has got quite a bit of uncertainty, and therefore predicting their changes often leads to a herculean task. Activities providing net return are influenced by the changing climate depending upon variable activities (Irland et al. 2001). Some activities such as fishing in cold-water stream, skiing in the snow and lake-based recreation may be severely affected as a consequence of the increasing temperature and climate change (Irland et al. 2001; Alig et al. 2004; Yadav et al. 2017).

In an Indian perspective almost half of the population is directly dependent upon fuelwood. It has been found that rural people are more dependent (65%) than urban people on fuelwood for cooking purposes (NSSO 2001). As per MoEF (2006) report, half of the fuelwood demand is being met up by natural forests, and the rest comes from farm forestry and extension forests. It has been found that there is sufficient amount of gap in demand and supply of forest resources which promotes unsustainable harvesting of woods (Khanduri and Mandal 2005; Aggarwal et al. 2009; Fig. 6).

As India is a land of domesticated animal, huge pressure is implied on pastureland also. This, therefore, causes destruction of grazing land by a huge amount of domesticated cattle which crosses the caring capacity (ICFRE 2001). Anthropogenic encroachment in the forest area also promotes unsustainability in the forest ecosystem (MoEF 2006). Various activities, i.e. grazing, trampling and lopping, significantly affect the regeneration potential of forest species and cause local biodiversity loss (Raj et al. 2018b) (Table 4). Considering the problems, SFM practices need to be implemented throughout the country in order to promote forest conservation on one hand and protect forests from various disturbances (natural or anthropogenic) on the other. Therefore, various practices such as integrated system of agricultural and forestry practices in the form of agroforestry, farm forestry and social forestry can be applied for solving the two-dimensional problem in the forestry sector (Jhariya et al. 2015). From a management perspective in India, it is reflected that the

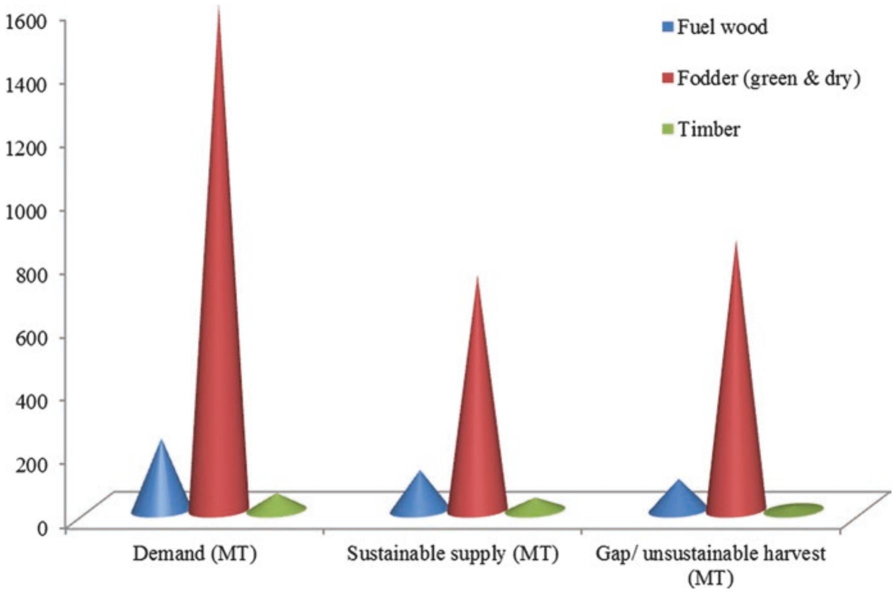

Fig. 6 Forest products demand-supply gap: Indian perspective. (Aggarwal et al. 2009)

government department has maximum contribution in forest management practices, and joint collaboration between government and local community stakeholders is much lesser than government institutions. The least management support was found from the private sector (Fig. 7, MoEF 2006). SFM jointly addresses the issues of forest and biodiversity conservation on one hand and livelihood security of the local community stakeholders on the other. Further SFM maintains the ecological health and process in forest ecosystem (Fig. 8).

9 Policies Towards Sustainable Management

Mitigation and adaptation to climate change through forestry application have always been correlated with policy issues. This includes an integrated approach which helps to serve the purpose of environmental conservation and protection. However an additional support in financial terms is required. The major problem associated with this is financial crisis in the forestry sector because there is no proper budget allocation. However, India is taking initiative in this respect as per the reports of 14th finance commission that proper budget allocation for individual state to increase the forest cover (GoI 2015). This approach also helps for ecological restoration of forest in different areas because almost half of the India's forest area belongs to open forest as well as anthropogenic pressure and improper regeneration become highly degraded (FSI 2013).

MoEF (2006) reported that up to 300 million human populations depend upon forest resources for their livelihood management. It is very surprising that forest

Table 4 Climate change-induced threatened tree species under red listed categories in the world (Newton and Oldfield 2008; Gonzalez-Espinosa et al. 2011)

Climate-induced red listed categories	Regions				
	Central Asian region	Ethiopia (African country)	Republic of Cuba	Meso-American dry forest	Montane tropical forests of Mexican region
Critically endangered (CR)	Twenty-five (25)	Forty-two (42)	Seventy-three (73)	One (1)	Eighty-three (83)
Endangered (E)	Twelve (12)	Thirty-five (35)	Twenty-three (23)	Seventeen (17)	Two hundred six (206)
Vulnerable (V)	Nine (9)	Twenty-eight (28)	Seventeen (17)	Twenty-four (24)	One hundred seventy-five (175)
Least concern (LC)	Twenty-five (25)	Nineteen (19)	Eight (8)	Four hundred fifty-seven (457)	Two hundred fifteen (215)
Near threatened (NT)	Eight (8)	Nine (9)	Two (2)	Thirty-nine (39)	Seventy-eight (78)
Data deficient (DD)	Eighteen (18)	Two (2)	Two (2)	Six (6)	Two (2)
Not evaluated (NE)	Not reported	Zero (0)	Not reported	Not reported	Zero (0)
Total	Ninety-seven (97)	One hundred thirty-five (135)	One hundred twenty-five (125)	Five hundred forty-four (544)	Seven hundred sixty-two (762)
Threatened percentage	Forty-seven (47%)	Seventy-eight (78%)	Ninety (90 %)	Eight (8%)	Sixty-one (61%)

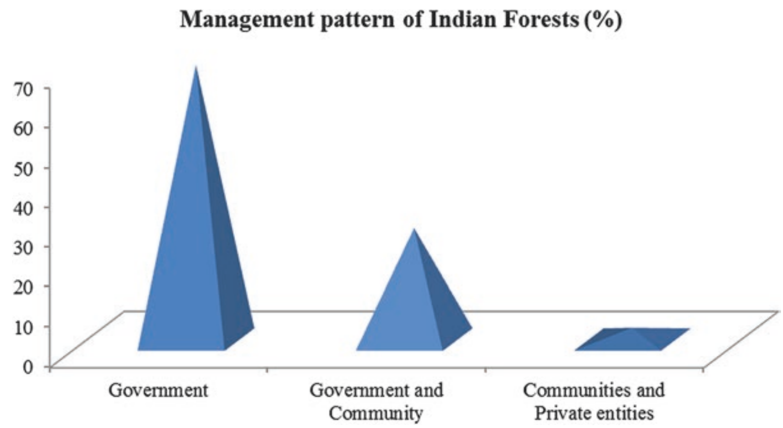

Fig. 7 Management pattern of Indian forests. (MoEF 2006)

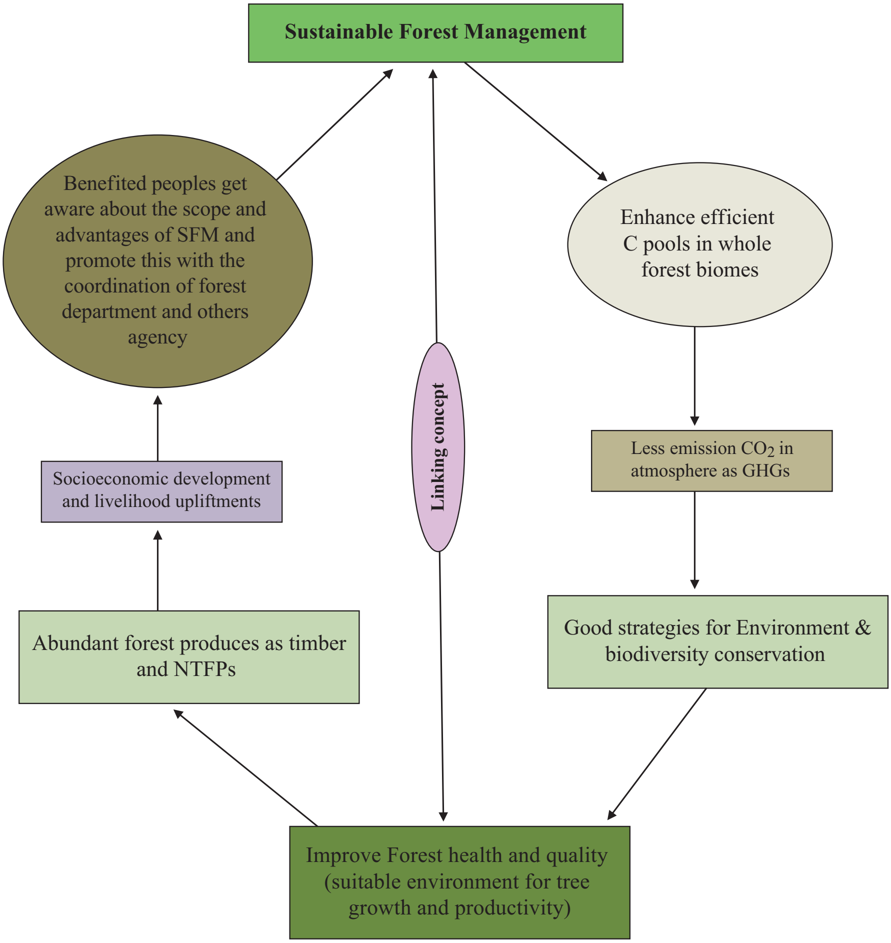

Fig. 8 Role of SFM in biodiversity conservation and livelihood upliftments. (FAO 2006, 2016; UN 2017; Pirlot et al. 2018; D'Aprile et al. 2015)

dweller and those who depend upon forest resource are still in search of security in terms of ownership of land and resource since India became independent. After the inception of Forest Rights Act 2006, people are eagerly waiting for their right over forests. Regarding implementation of this act, issues such as right recognition and site and individual selection are a big challenge (MoEF and MoTA 2010). However, the Indian government has brought amendment in 2012 to resolve the issues such as livelihood dependency and rights of the community people. As per the records of MoTA (2015), 1.56 million claims settlement regarding forest right encroaching up to 4% of area has been completed. In this connection, tribal states such as Chhattisgarh and other states such as Rajasthan and Orissa have revealed almost cent percent individual and 0.4% community rights, respectively.

For SFM, proper forest inventory along with information related to structure, composition of vegetation, sampling process and quantification methods acts as the principal source of forest information. This also frames the base of C stock and wood biomass stock and annual increment of forests. Competent forest inventories and information at the national level need to be upgraded through using advanced technologies such as remote sensing. Further C stock in wood products needs to be monitored in order to use forests as a tool for combating climate change. While thinking about SFM, good governance, suitable policy formulation and strategy development aiming towards adaptation and mitigation of climate change need to be built up both at the national and international level. One of the key issues includes interlinkage between forests and other sectors towards adaptation to climate change (Fig. 9).

During the British rule, forest was considered as an economic resource to provide raw material for mankind. As a consequence, at that time forest was simply a timber-yielding production system. But the scenario changed after independence through formulation of NFP (National Forest Policy) 1952, where the focus was given to the ecological integrity as well as fulfilling human needs. Afterwards, with the passage of time, a new forest policy was formulated in the year 1988 considering the ecological, economic and social dimensions of sustainable development. Therefore the urgent need for the implementation of sustainable policies is being established. In recent times a change in paradigm from consumeric forestry approach to sustainable forestry approach has taken place. However, sustained yield seems to be the principle objective on modern scientific basis which forms the central theme of organized forestry approach.

Strategies aiming towards SFM should address for development of technologies that promote lesser impact of climatic events, reduce risks of climate change and arrange the ecosystem to work as climate shocks. Ecosystem-oriented approaches include conservation and restoration of degraded forest land along with climate change adaptation (IUCN 2008). All these issues can be addressed under national policies that would raise social awareness in terms of recognizing values of forest ecosystem services (Vignola et al. 2009).

10 Future Prospectus of Forest and Climate Research and Development

Future exploration is still awaited towards identifying the possible vulnerable issues in terms of having negative impacts due to climate change. It is a big challenge to manage issues like pest infestation, disease outbreaks and genetic resource development along with maintaining forest ecological values. Integrated and interdisciplinary works need to be addressed in this field. Another essential mandate is that SFM should be brought under the banner of political framework for effective adaptive implementation of SFM policies (Fig. 10).

From a world perspective, the impacts of climate change are still under uncertainty in many areas of Asian subcontinents. Projections related to precipitation

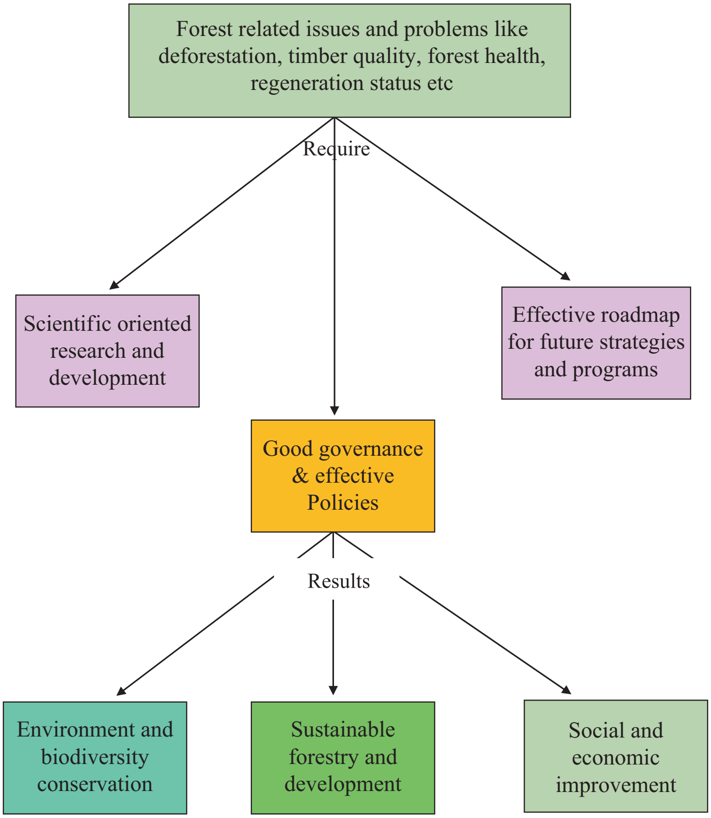

Fig. 9 Policies for SFM. (Pirlot et al. 2018)

pattern and supply of water are the most urgent need in order to sustain forest. The major limitation regarding information about climate change impacts in Asia is due to inadequate information about biodiversity (UNEP 2012). Very interestingly proper inventories of biodiversity at the national level are scarce resourced, and even in some cases, baseline information is inadequate. Further for tropical condition issues such as the influence of temperature for C fixation in tropical plants and thermal resilience, the impact of increase of ambient CO_2 level is a big knowledge gap (Zuidema et al. 2013).

Dynamics of the boreal biome depends upon various interactions between increase in temperature and ambient CO_2 level. Further natural events and insect infestation also may influence such dynamics (Zhang et al. 2011; Kumar et al. 2017). To have a detailed idea about interrelationship between climate change and forest dynamics, information related to species composition and biology along with modelling (ecological and environmental) would become very much essential (Meleshko and Semenov 2008). A wide lacuna in knowledge exists in the area of climate change predictability and associated impact over forests of different

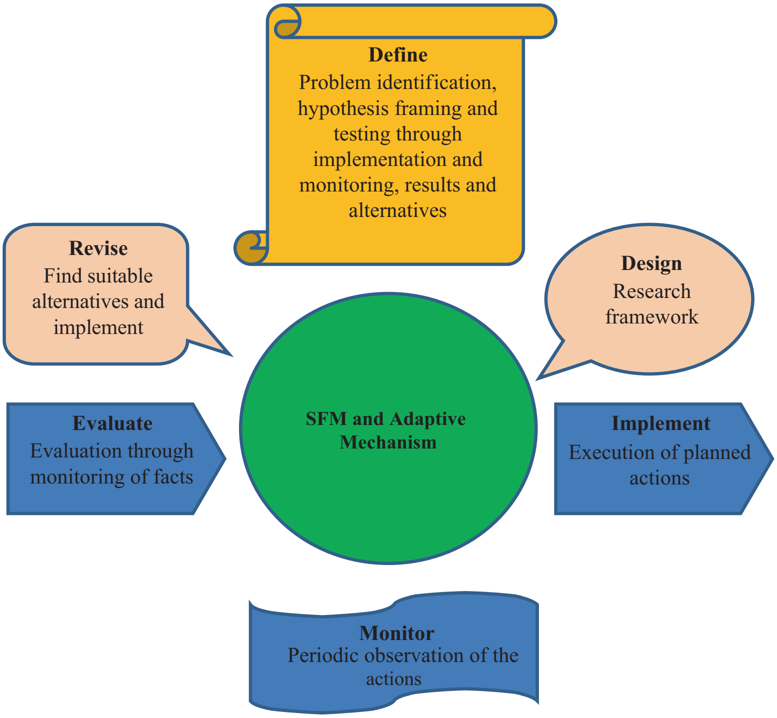

Fig. 10 The SFM and adaptive mechanism. (Murray and Marmorek 2004)

countries. Database in relation to elevated temperature needs to be procured for further improvement in the future trend of the changing climate which incorporate local issues such as region-specific conditions, nature of forest produce, genetic resource base and various values of forests.

SFM includes ecosystem-oriented approach which should incorporate programmes related to forests at the national level, development of model forests and various certification systems. SFM is such an approach which includes integration at the cross sectoral and inter-sectoral level which involves people, forests, habitat and biodiversity. Climate change mitigation in forestry sectors is very much economy oriented due to livelihood generation for rural people. Forest ecosystem plays a multidimensional role through GHG emission reduction, C sequestration and reducing the risk on people and ecosystem towards climate change. Throughout the world, the major aim should be to control the loss of forests. In this context, suitable management strategies for forest conservation would be highly fruitful. Scientific exploration and proper research road map need to be designed in these areas for utilizing forests towards mitigating climate change.

From an Indian perspective, one has to face severe challenges in terms of policy implementation in the forestry sector. Therefore, policies should be aimed towards controlling of forest depletion, reducing impact of climate change on forests and providing livelihood sustainability throughout the country. It has been observed that the gap between demand and supply of forest products is imposing negative consequences in the forestry sector. Policies can be formulated on time span basis (short-, mid- and long-term) depending upon the prevailing scenario. Research investigation towards the changing climate and degradation of forests may incorporate the development of vulnerability index for forests which includes clear databases related to density of forests and biodiversity along with shifting of vegetation type in the near future. Such studies revealed that the northern and central part of Western Ghats hills along with the upper part of the Himalayas would be highly vulnerable in this context and vegetation of the northeastern region would act as ecologically resilient (Chaturvedi et al. 2010).

From a short-term perspective, collaboration between education institutes, forest department and private organization is very much essential to produce sustainable resource base. In this connection, India has already progressed through its 5-year plan to establish nurseries in selected forest zone. NFP of 1952 and 1988 has emphasized to increase the forest cover, but mere 5.71 million hectare areas reflected an increment of forest cover for the last 28 years (FSI 2013). As per forest policy, the target of increasing forest cover up to 33% is merely theoretical under the pressure of modernize society, and therefore, the government has modified the aim by increasing up to 5 million hectare under the 5-year plan (Planning Commission 2013). Of this 5 million hectare, 2 million hectare would be in the form of extension forestry or afforestation scheme and 3 million hectare in the form of reforestation. The energy sector has a big role to play in this connection towards rural community. The expansion of liquid petroleum gas distribution in the rural livelihood along with the promotion of using improved chullahs may bring the benefit by saving up to 400 kg fuelwood per annum.

The World Bank report (2006) revealed a higher economic gain in terms of ecotourism operation in various joint forest management areas. Ecotourism can be judiciously promoted through involvement of private sector and local community people which would work in the direction of capacity building. Identification of community rights through proper legal procedure should be promoted, and subsequently illegally occupied areas should be cleared. Bottlenecks of the forestry sectors should be properly taken care for promoting SFM. For instance monitoring over government revenue earning through forests produce, strict implementation of laws, allotment of credibility to the poor people along with proper valuations are some of the major issues. Local people should be trained on these aspects to make them participate in the value addition process. Addressing climate change in the forestry sectors needs awareness creation among the staff of forest department along with local people to make climate adaptation successful. In this process arresting forest fire and fragmentation of forests may be implemented.

From a midterm perspective, some areas can be improved through mixed plantation with subsequent natural regeneration of vegetation. Additional area can be procured through plantation in the common and private lands under various schemes such as agroforestry and social forestry. Restriction over felling and transportation of agroforestry species should be mediated through legal means and promote local species plantation on private lands. Strengthening and upgradation of knowledge base in terms of advanced agricultural practices, animal husbandry and SFM should be inculcated among the local stakeholders for livelihood improvement. The focus is on NTFP collection and marketing under the joint collaboration between community stakeholders and private organization. Cooperative formation in this context for proper evaluation of NTFPs is a very fruitful step. Gram panchayat should be actively involved in this matter, and green funds should be raised to promote green volunteers to work for natural resource management. Scientific information on climate change impact on structure and ecological services of forests should be integrated with SFM.

From long-term perspectives, forest cover can be increased through various plantation schemes and by natural regeneration process. Promoting the use of alternate energy sources and liquid petroleum gas sources may help to reduce the pressure of forest dependency. The concept of joint forest management should be modified in the form of community forest management under which gram panchayat will play the key role and forest department would monitor the efficient implementation of different policies. Simultaneously forest enterprises at the small level should also be promoted which may contribute significantly towards livelihood improvement. Findings of the research programmes from climate change adaptation perspectives should be integrated with forest management and working plan. Overall climate change adaptation should include information related to the influence of changing climate on forests and changing pattern of vegetation along with SFM.

11 Conclusion

The most interrelated issue in modern context is the changing climate along with managing sustainability of natural resources. Vegetation plays a diverse role for the survival of human being and biodiversity. Due to climate change, forests are now becoming under severe threats of depletion, and as a consequence, human civilization would be starving for the services of forests. Forests provide resources in the form of livelihood under changing climate which would support the sovereignty of forest dwellers. As the whole world is changing under the impact of climate change, therefore multiple uses of forests would be the need of the hour. For effective management community participation, industry-institute-local stakeholders-government partnership and capacity-building policies need formulation towards achieving sustainability. From a changing climate perspective, mitigation with adaptation is required to run simultaneously by adopting SFM strategies. SFM strategies include practising processes that promote more C sequestration, and more ecosystem resilience. Simultaneously sustainable harvesting and lesser resource dependency generation through alternate practices such as agroforestry, farm forestry, social forestry, extension forestry and NTFP production and marketing would act as suitable SFM. However there are some key challenges that may hinder the effective implementation of SFM strategies. Small landholding, lack of technical expertise, less efficient marketing mechanism and lack of funding are the principal obstacles that hinder effective management of forests aiming towards mitigating climate change. Due to severity of climate change, one has to opt for SFM practices due to their multidimensional role. SFM practices promote biodiversity conservation, provide livelihood for local community stakeholders, maintain ecological integrity, promote forest conservation and restoration and therefore support human civilization for their prosperity. Policy formulation would be very important from a climate change perspective in the form of risk management to be incorporated under the planning of SFM.

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Ecosystem Services of Trees Outside Forest

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Contents

Abstract

Trees or other woody vegetation growing outside designated forest areas are known as trees outside forest (TOFs). These trees have many ecosystem services and economic benefits like their potential role in agriculture, food supply and income by providing goods and services, conservation of biodiversity and carbon (C) sequestration. They can improve soil fertility through fixing atmospheric nitrogen, retaining soil moisture, regulating water shed, reducing topsoil loss and litter fall and regulating microclimate, thus increasing crop yield. In addition to providing aesthetic beauty especially to urban surroundings, they are pollutant sink, reduce ozone levels, check dust flow, reduce noise pollution and cools air temperature. Most importantly, these trees are useful timber resources and will

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alleviate pressure on native forests. Forest and TOF are thus considered as two faces of a coin in relation to their capacity for C stock and biodiversity. Substantial amount of trees are going on lands other than forest land used in every country with a potential of sequestering about 38 giga tonnes of C annually. In India, for example, there are about 24–25 thousand million TOFs, out of which trees in agricultural landscape in Indian state of Uttar Pradesh only sequester 20 million tonnes of C. The C sequestration potential of the TOFs is thus enormous to be included in global climate mitigation strategy through reducing emission from deforestation and forest degradation (REDD+) activities. Moreover, as these are additional plantations, so are they complementary with other land uses in mitigating climate change. Unfortunately, due to absence of efficient inventory methods, TOFs are still not accounted fully in the national forest inventories, due to which very less or no information are available for TOFs. Accounting TOF and its services will not only help to understand its importance for national C budget but also its ecological and economic role benefiting human society.

Keywords
Biomass · Climate change · Diversity · Ecosystem services · Tree outside forest

Abbreviations

CDM	Clean development mechanism
C	Carbon
CO_2	Carbon dioxide
FAO	Food and Agricultural Organization
FSI	Forest Survey of India
NFI	National Forest Inventory
NFMA	National Forest Monitoring and Assessment
TOFs	Trees outside forest
REDD	Reducing emission from deforestation and forest degradation

1 Introduction

Global climatic change and biodiversity loss are major concerns in terms of sustaining future generations and a debatable issue among the global scientific community and policymakers (Zhang et al. 2011; IPCC 2013; ter Steege et al. 2013; Jhariya 2017; Raj et al. 2018a, b). Agro-forests, community forests, village woodlots, road side plantation, urban plantation and other trees outside forest (TOFs) are also pivotal in combating global climatic change and reduce biodiversity loss and can be effective segments of sustainability (Roshetko et al. 2007; Kumar and Nair 2011; Meena et al. 2018; Jhariya et al. 2018). Forest is not all trees and all trees are not forest. Huge amount of tree resources exist in almost all the countries but generally were ignored, and attention is given to forests only. However, from a past decade or two, the ecological and societal benefits of TOF are gaining recognition (Schnell 2015). Schnell (2015) reported that TOF was much mentioned as early as seventeenth century in the book *Silvicultura Oeconomica* by Carlowitz (1713). However, tree has been associated with human civilization outside forest from time immemorial in the form of agroforestry and urban plantations, and abundant TOF inventories have been reported after this book though ignored till Food and Agricultural Organization (FAO) recognition in the 1990s (Boffa 2000; Herzog 2000; Bellefontaine et al. 2002; Pain-Orcet and Bellefontaine 2004). FAO coined TOF during preparation of the Global Forest Resources Assessment 2000 report (Pain-Orcet and Bellefontaine 2004) to increase political attention on TOF (de Foresta et al. 2013).

The basic definition is TOFs are 'trees growing outside forest or other wooded land' (Bellefontaine et al. 2002; Schnell 2015; Yadav et al. 2017a). TOF in India according to Forest Survey of India (FSI) is defined as 'all those trees, which have attained 10 cm or more diameters at breast height, available on lands, which is not notified as forests' (FSI 2013). Definitions of forest vary from country to country and so TOF also (Lund 2002). So, the internationally accepted and applied definition is that of FAO which defines 'TOF as trees available on lands which is not defined as forests or other wooded land' (FAO 2005, 2010; Kumar 2006). The word 'trees' in the FAO definition also includes shrubs, palms and bamboo (de Foresta et al. 2013). TOFs are trees growing both in rural and urban areas on farms, common lands and waste lands and along roads and railway tracks and institutions (FAO 2001a; Bellefontaine et al. 2002, Tamang 2018). Trees outside and inside forests are similar in many ways (McCullough 1999).

In areas where there is no or less forest, the ecological and economical role of TOFs can be pivotal (FAO 2001a; Bellefontaine et al. 2002). TOFs can aid in sustainable development through conserving biodiversity in an agricultural-dominant landscape providing resource base upon which our future generations depend (Pushpangadan et al. 1997). In complementary to the ecological and economical role of forest, these trees store enormous amount of carbon (C) in their biomass, thus can sustain the carbon dioxide (CO_2) balance of the atmosphere. In addition to this role, TOFs can substantially meet the growing wood and wood product demands, thus reducing deforestation promoting sustainable development. Maintenance and periodic assessment of diverse ecosystems and a whole range of biological diversity therein are, therefore, crucial for long-term survival of humans (Berkes et al. 1998; Ayensu et al. 1999). Evaluation of TOF structure and function is needed to understand its status and dynamics (de Foresta et al. 2013; Singh et al. 2017). Tree species richness in any area develops the locality factors for other organisms to develop and breed and its role in increasing biodiversity (Gene et al. 1978). TOF can also be critical in sustaining agriculture, food security, household economy and supply of many products and services apart from being reservoirs of ecological functions like conservation of biodiversity, C sequestration climatic stabilization and livelihood support in rural and urban areas (Rawat et al. 2004; FAO 2005; Acharya 2006;

Kumar et al. 2017). However, to realize full potential, TOF needs holistic management approach of resource management locally, regionally and globally (Bellefontaine et al. 2002). This requires efficient inventorying methods integrated fully with the national forest inventories. The chapter thus briefs the need of TOF accounting and underlines its services to understand its importance for national C budget along with its ecological and economic role benefiting human society.

2 TOF Classification

TOF by definition consist of tree formations with varied functions and arrangements, making classification difficult (Kleinn 2000). Such classifications are based on origin, land use, geometry and function of the trees (Bellefontaine et al. 2002). FAO also recognized three distinct TOF types as TOF on agricultural, urban and non-urban non-agriculture land (FAO 2012; Yadav et al. 2017a). TOF on urban land are trees and/or shrubs growing in gardens, parks, parking lots, along streets and others. TOF on agriculture land include trees and/or shrubs growing on lands under agricultural land use. Agroforestry systems, non-forestry tree crop plantations and orchards are included in agricultural land use. Trees growing on natural lands like grasslands, tree line in mountainous areas and peat lands are categorized as TOFs other than urban and agricultural lands. TOFs on non-agricultural/non-urban land have trees and/or shrubs growing on lands other than agricultural or urban land use, i.e. outside forests. TOFs growing isolated or scattered, in groups and linearly, are categorized based on spatial arrangement (Alexandre et al. 1999). TOFs are also classified functionally like production (food, fodder, firewood), protection (windbreaks, erosion checks), ornamental and aesthetic purposes. Classification of TOFs based on origin is based on whether trees are planted or are leftover of former forests. The trees leftover of a former forest is reported from Latin America where virgin forests are harvested (Kleinn 1999).

3 Ambiguities in TOF Classification

Sometime TOF cannot be distinctly classified from forest as for grasslands or pastures and commercial plantations with shade trees and orchards (Kleinn 1999). de Foresta et al. (2013) also reported problems classifying trees under shifting cultivation, rubber plantations and linear formation and in some agroforestry practices as TOF. Shifting cultivation fallow period follows after a crop period when vegetation regrows making it debatable whether the land is forest or abandoned land after agricultural use. Trees are thus falsely classified either as forest or TOF on such land. Agroforestry in forest land use where temporary grazing is permitted or interculture of annual crop is permitted during early age of forest plantations are not TOF (Schnell 2015). Rubber plantations are also debated, earlier considered as agricultural land use but now recognized as forest (de Foresta et al. 2013).

Classifying linear tree formations in non-agricultural or non-urban also creates problem after FAO included trees either growing in lines having more than 20 m width or in land with area of more than 0.5 ha as forest (Schnell 2015). Moreover, the definitions and meaning of agricultural and urban lands vary from country to country (de Foresta et al. 2013). Sometimes, urban forest is not all included in urban land use but those within and close to the urban areas, i.e. partly in forest land use also (Konijnendijk 2003). In such a case, Rydberg and Falck (2000) recommended considering ground vegetation as a basis for classifying, i.e. uncultivated land as urban forest and cultivated as TOF.

4 TOF and Sustainability

The ecosystem services and economic benefits associated with these trees have begun to attract more attention towards them (Singh and Chand 2012; de Foresta et al. 2013). The trees fix atmospheric nitrogen in the soil and aid in nutrient cycling through litter fall, increasing fertility and thus crop yield. Trees help to retain moisture in soil and topsoil by reducing soil evaporation, checking erosion and reducing water flow. Trees regulate and maintain watershed-building materials. Trees act as a live fence in form of windbreaks and shelterbelt performing protection function. Interest is growing among researchers and policymakers to promote green spaces in urban areas to curb negative impact of urbanization on biodiversity and humans (Shwartz et al. 2014). Moreover, these plantations ensure continuous tree cover to attain benefits for current and future generations (Ajewole 2010).

Every country has extensive tree wealth outside continuous forested areas, and they make important contribution to sustainable agriculture and supply many products similar to forests (Yadav et al. 2017b). TOF include urban and other plantations like road side, homestead gardens, residential areas or in various institutional or academic landscapes. They form important green region in urban and industrial sectors (Schnell 2015, Yadav et al. 2017a; Tamang 2018). An important feature of urban landscape is its trees growing along the roadside or streets (Houde 1997; McPherson and Luttinger 1998). These trees give aesthetic beauty to an urban surrounding providing psychological harmony to the urban residents (Kuchelmeister and Braatz 1993). Several studies also have highlighted these trees as an important feature of rural landscapes (Bellefontaine et al. 2001; Gutzwiller 2002; de Foresta et al. 2013; Datta et al. 2017). These trees are planted widely in all physiographic regions of the globe with socioeconomic and ecological implications (de Foresta et al. 2013). The green spaces are useful for different habitats, provide cultural services and promote human well-being making positive contribution to living conditions of different towns and cities (Mitchell and Popham 2008; Bowler et al. 2010; Arnberger 2012; Buchel and Frantzeskaki 2015).

Trees in urban landscape not only have aesthetic value but make these localities serene and green for agreeable places to work and live. Studies reported a concept ‘proximate principle’ (Table 1) wherein people are willing to own a property in a greener and open locality even with higher price (Wolf 2005, 2007; Chaudhury 2006).

Table 1 Proximate principle

Property value hike	Location of property
10%	Within ¼ mile (0.4 km) of a park
20%	Near to or facing a park
32%	Within or close to green belts

These trees are useful timber resources that will alleviate the pressure on native forests; nutrient cycling and CO_2 sink (Chavan and Rasal 2010; Curlevski et al. 2010; Mandal and Joshi 2014; Nowak et al. 2018). The consequences are reducing the pressure on natural forest in one way and C enhancement and species diversity in other way (Singh and Lodhiyal 2009; Thompson et al. 2009; Singh and Chand 2012). This satisfies the objective of reducing emission from deforestation and forest degradation (REDD+) mechanism. Therefore, forest and TOF are considered as two faces of a coin in relation to their capacity for C stock and biodiversity (Kleinn 2000). The C sequestration potential of these plantations is also high enough to be included in global climate mitigation strategy. These are additional plantations and so are complementary with other land uses (Schoeneberger 2009; Plieninger 2011; Thangata and Hildebrand 2012).

Urban trees and plantation along the road and canal side can act as sink for pollutants; reduce urban O_3 levels; check dust flow, fly ash and noise pollution; cool air temperature; and provide aesthetic beauty to the urban landscape (Chavan and Rasal 2010; Nowak et al. 2018).TOFs are ecologically important for urban localities as they fix atmospheric C in their biomass, modify microclimate, fix airborne pollutants and control storm water runoff (Rowntree and Nowak 1991; McPherson 1994; Srinidhi et al. 2007). Road side trees are more efficient to fix particulate matter than other trees and thus are critical in controlling point source pollution (Beckett et al. 2000). Short-rotation trees, i.e. eucalyptus (*Eucalyptus* spp.), poplar (*Populus* spp.), willows (*Salix* spp.) etc., are the most commonly employed trees for combating toxic chemicals and keep intrusion of pollutants away from the food chain. Other important trees are neem (*Azadirachta indica*), siris (*Albizia* spp.), kassod (*Cassia siamea*), silver oak (*Grevillea robusta*), etc.

TOFs are valuable vegetation C pools and plant biodiversity or microhabitat centres and are critical biodiversity hotspots (Kharal and Oli 2008; Oleyar et al. 2008; Jim and Chen 2009; Goddard et al. 2010). Isolated trees and urban woods have cultural and socioeconomic with aesthetic and recreational values as well (Herzog 2000; Tyrvainen et al. 2005; McDonnell et al. 2009; Grala et al. 2010; Buragohain et al. 2017). Their importance is recognized now due to biodiversity loss, desertification and poverty alleviation. These plantations have the potential to provide ecosystems services in the form of preventing soil erosion, removing air pollutants, modifying microclimate and soil properties, nutrient and water cycling, regulating water flows, biodiversity conservation, pest control, food or fodder and wood products (Baudry et al. 2000; Verma 2000; Chiesura 2004; Plieninger et al. 2004; Lumsden and Bennett 2005; Ahmed 2008; Bhagwat et al. 2008; Pandey 2008; Jim and Chen 2009; Manning et al. 2009; Bowler et al. 2010; Paletto and Chincarini 2012; Ament and Begley 2014).

5 Diversity, Biomass and C Stock of TOF

Deforestation and climate change has threatened extinction of about 8000 tree species, or 9% of the total global tree species (Singh et al. 2005; FAO 2010). Assessing plant diversity, its management and sustainable utilization requires proper documentation and quantification of qualitative and quantitative parameters of plant community (Jayanthi and Rajendran 2013; Padalia et al. 2014; Rajendra et al. 2014). The cultural, socioeconomic and ecological potential of TOFs was increasingly recognized after the mid-1970s with popularization of tree planting programmes mainly outside forests. These programmes were initiated mainly to meet the growing demands of wood and its products along with reclamation of problematic lands and maintaining ecological health (Nair 2012). Plantation of trees outside forest has been playing positive roles in C enhancement and biodiversity conservation (Leah et al. 2010). There are many reports on plant diversity and C stocks from areas outside forest especially from institutional landscapes (Dubal et al. 2013; Suryawanshi et al. 2014; Tiwari et al. 2014; Thankappan et al. 2015; Ranjan et al. 2016; Sharma and Ekka 2016).

These institutional areas generally have large vegetative areas supporting excellent tree cover which can counter balance C emissions through C storage and sequestration (Gavali and Shaikh 2016; Singh et al. 2017). C capture rates of these landscapes vary with locality factors and management practices (Rahman et al. 2015). Studies on vegetation cover from various universities and roadside plantations have documented species richness, dominant species, plant population and uses along with tree biomass and C storage (Baral et al. 2013; Rajendra et al. 2014; Suryawanshi et al. 2014; Tiwari et al. 2014; Rahman et al. 2015; Singh and Singh 2015; Gavali and Shaikh 2016; Sharma and Ekka 2016; Singh et al. 2017; Varma et al. 2017). Deforestation can be checked by extensive plantations of trees in such landscapes which will reduce the pressure on natural forest as these trees have the potential to meet the demand of wood and its products.

Studies also reported potential of orchards for C cycling, storage and net CO_2 flux (Sekikawa et al. 2002; Sofo et al. 2005). Orchards are similar to forests in terms of C sequestration during its initial years of establishment (Kerckhoffs and Reid 1997). Fruit tree-based plantations in southern Philippines were reported with a C storage of 112.18–203.62 tonne/ha (Janiola and Marin 2016). Fruit trees with diameter more than 30 cm in certain land use make large contribution to total C stock, and the above-ground components especially the fruit trees show the greatest amount of biomass and C (Janiola and Marin 2016). Orchards store C in their woody biomass, and it can also be viable strategy for climate change mitigation in an agricultural-dominant landscape. Forests and also TOFs in the developing countries coexist with smallholder farming systems including agroforestry, thus sustaining smallholders and diversity as well in an agricultural-dominant landscape (Gilmour 1997; Regmi 1998; Garforth et al. 1999; Baral et al. 2013). In addition, agroforestry systems are also efficient C sink in human-dominated landscapes especially in the urban areas (Bhagwat et al. 2008; Kharal and Oli 2008; Pandit et al. 2014). The major social and agroforestry tree species in India are eucalyptus, babool (*Acacia* *nilotica*), poplar, maharukh (*Ailanthus excelsa*), bakain (*Melia azedarach*), willows, shisham (*Dalbergia sissoo*), subabul (*Leucaena leucocephala*), gamhar (*Gmelina arborea*), beach oak (*Casuarina equisetifolia*) and white locust tree (*Robinia pseudoacacia*) grown on about eight million hectares area (Chauhan et al. 2008; Dogra and Chauhan 2016).

Commercial plantations of cacao (*Theobroma cacao*), tea (*Camellia sinensis*), rubber (*Hevea brasiliensis*) and others are reported to restore C stocks after replacement of the native forests (Sonwa et al. 2009; Oke and Olatiilu 2011; Norgrove and Hauser 2013; Dawoe et al. 2016). Forest and tree plantation have the capacity to store more C than other types of vegetation (Lasco et al. 2002). The long life span of these plantations makes them potential C sink under different ecosystems (Cotta et al. 2006; Ranasinghe and Silva 2007; Ranasinghe and Thimothias 2012). Controlling the present level of atmospheric CO_2 through REDD+ activities is the most viable and feasible strategy recommended by scientists and policymakers (Kanowski et al. 2011; Pandey et al. 2014; Rahman et al. 2015; Yadava et al. 2017), and trees outside forest efficiently can fulfil the objectives of this strategy (FAO 2006; Canadell et al. 2007; Lewis et al. 2009). This is because of positive relationship between species diversity and total biomass reported for these plantations (Singh and Singh 2015; Jhariya and Yadav 2018).

Globally there is very less or no information available on TOF resources that too are rarely integrated with national forest inventories. This is because till date there are no efficient methods of inventorying TOF resources, except for a recent analysis of existing data from available country-level TOF inventories by Schnell (2015). This analysis reported that in the analysed countries, TOFs contribute substantial amount of biomass and C to national stock. The result of this work will be a way forward from forest centred to all trees including TOFs that are valuable resource economically and ecologically. The analysis concluded that forest- and tree-based land uses of the studied countries varied extensively (Table 2).

Kyrgyzstan, Bangladesh and Lebanon were reported with lowest forest cover but has highest OL indicating land use category where TOF grows. In continuation of

Table 2 Area of TOFs and forest (Schnell 2015)

Country	Forest	Other wooded land	Other land
Bangladesh	8.1[a]	0.7	76.8
Cameroon	44.2	31.1	23.5
Costa Rica	46.7	1.8	43.1
The Gambia	26.6	10.9	52.1
Guatemala	37.3	16.3	42.6
Honduras	42.7	11.7	34.7
Kyrgyzstan	3.4	3.1	88.8
Lebanon	12.6	10.4	71.7
Nicaragua	25.0	17.0	48.8
Philippines	23.8	12.2	61.3
Zambia	63.9	7.4	19.7

[a]Figures are per cent of total land area

Table 2, Table 3 presents the live above-ground tree biomass of TOF of the countries in comparison to its forest (Schnell 2015).

Six countries were estimated with above 10% of their total tree biomass contributed by TOFs, and exceptionally high contribution (73.2%) was reported from Bangladesh (Schnell 2015). Significant amount of TOF (more than 80%) was found by Schnell (2015) growing on agricultural land (Table 4).

About 49 million trees on private land were reported from Gujarat state of India (GoG 1984). Farmlands in India were estimate with a total of 16,578 million trees (Kotwal and Bhattacharya 2000). National assessment of trees outside forest estimated between 24,000 and 25,000 million trees in India (Prasad et al. 2000). A total of 671,852 trees of teak (*Tectona grandis*), 483,876 trees of mango (*Mangifera indica*), 288,995 trees of shisham, 99,053 trees of neem, 36,748 trees of jackfruit (*Artocarpus heterophyllus*) and 68,909 tree of babool were inventoried into

Table 3 Estimated above-ground biomass (Schnell 2015)

	Forest		Other wooded land		Other land	
Country	AGB	PTTB	AGB	PTTB	AGB	PTTB
Bangladesh	33.4	26.7	7.7	0.5	9.6	72.8
Cameroon	159.9	89.4	14.6	5.8	16.4	4.9
Costa Rica	104.0	93.0	0.0	0.0	8.5	7.0
The Gambia	21.8	57.6	8.0	8.7	6.5	33.7
Guatemala	80.6	86.0	9.3	4.3	7.9	9.6
Honduras	79.2	91.0	9.3	2.9	6.5	6.0
Kyrgyzstan	30.2	84.2	1.0	2.6	0.2	13.2
Lebanon	24.6	51.6	4.6	7.9	3.4	40.5
Nicaragua	74.1	74.4	12.6	8.6	8.6	17.0
Philippines	82.6	69.0	10.5	4.5	12.3	26.5
Zambia	32.0	95.1	4.9	1.7	3.6	3.3

AGB above-ground biomass expressed as Mg ha^{-1}, *PTTB* proportion of total tree biomass of the studied country expressed as per cent

Table 4 Distribution of trees outside forests (values in %) (Schnell 2015)

Country	Natural	Agriculture	Settlement
Bangladesh	0.0	16.0	84.0
Cameroon	17.6	80.7	1.8
Costa Rica	0.0	96.4	3.6
The Gambia	17.3	82.1	0.5
Guatemala	10.9	83.2	5.9
Honduras	6.4	85.6	8.1
Kyrgyzstan	35.6	26.4	37.4
Lebanon	3.3	89.8	6.9
Nicaragua	2.7	93.5	3.8
Philippines	6.4	88.4	5.2
Zambia	30.0	62.7	7.3

different diameter classes for 66 villages of Gorakhpur district, Uttar Pradesh, in India (Srivastav et al. 2012). The total number of enumerated trees in this inventory for all six species with respect to diameter class is given in Table 5.

The study described above adopted a field survey method following stratified random sampling to select villages to enumerate number of trees. This study though classified tree based on diameter classes but did not monitor the biomass accumulated. Such studies are very laborious and time consuming. Biomass quantification is required to estimate C sequestration, so TOF inventory must include estimates of biomass and C storage in it. Stand-wise TOF inventory of Haryana, India, was made using finer spatial resolution of IRS-P6 LISS-IV satellite data (Singh and Chand 2012). Above-ground TOF biomass estimated for scattered trees was 1.26 tonnes/ha and for trees growing canal side was 91.5 tonnes/ha. The total above-ground TOF biomass and C stock estimated were 367.04 and 174.34 tonnes/ha, respectively (Table 6). The study shows that assessment of TOF biomass and its C accumulation can be successfully achieved by integrating GIS techniques, field data and high-spatial-resolution data of IRS-P6 LISS-IV for the larger areas.

Trees growing in agricultural landscapes improve productivity and create C sink as well. C accumulated by semiarid, subhumid, humid and temperate region of agroforestry land use system was 9, 21, 50 and 63 Mg C ha^{-1}, respectively (Schroeder 1994). In the next half a century or so, about 38 giga tonnes of C would be sequestered globally by afforestation/reforestation and agroforestry practices. About 20

Table 5 Diameter class-wise classification of tree species (Srivastav et al. 2012)

DC	M i	A i	D s	A h	A n	T g
0–50 cm	297,512	88,970	285,333	35,435	68,806	671,852
50–100 cm	186,364	10,083	3662	1313	103	0
Total no. of villages	9599	1965	5733	729	1367	13,328
Av. no. of trees/village	145	30	87	11	21	202
Total no. of trees	**483,876**	**99,053**	**288,995**	**36,748**	**68,909**	**671,852**

DC diameter class, M i *Mangifera indica*, A i *Azadirachta indica*, D s *Dalbergia sissoo,* A h *Artocarpus heterophyllus*, A n *Acacia nilotica*, T g *Tectona grandis*

Table 6 Tree density, biomass and C stock of TOF (Singh and Chand 2012)

TOFs	Number of trees[a]	Biomass[b]	C stock[b]
Linear		40.71	19.34
Road	171–1556	41.59	19.75
Rail	478–557	11.15	21.47
Canal	852–1440	45.21	5.30
Block	447–1200	18.24	8.66
Scattered		7.15	3.40
Urban	170–416	9.53	4.53
Rural	132–336	6.79	3.22
Agroforestry	64–164	6.33	3.10

[a]The figures are number of trees/ha
[b]The figures are in tonnes/ha

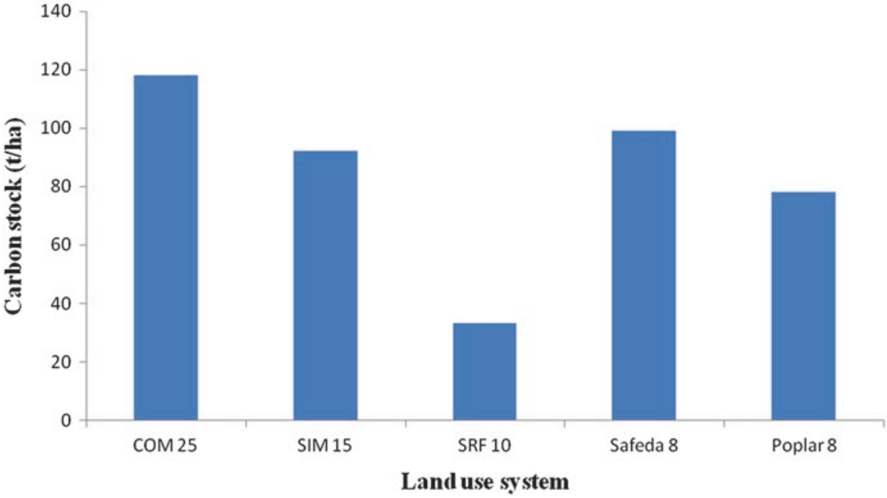

Fig. 1 Comparison of C stock in different land use systems. (Adopted: Dogra and Chauhan 2016) *Com25* complex agroforestry of 20–40-year rotation, *Sim15* simple agroforestry of 15-year rotation, *Safeda8* eucalyptus agroforestry of 8-year duration, *Poplar8* poplar agroforestry of 8-year rotation

Table 7 TOF biomass C stock in China (Guo et al. 2014)

Period	Woodlands	Shrubberies	Trees on non-forest land	Total
1977–1981	70 (8.5)[a]	335 (40.7)	418 (50.7)	823
1984–1988	74 (7.7)	350 (36.5)	535 (55.8)	960
1989–1993	69 (6.2)	374 (33.6)	672 (60.3)	1114
1994–1998	108 (9.0)	427 (35.7)	660 (55.2)	1195
1999–2003	97 (7.8)	512 (41.5)	625 (50.7)	1233
2004–2008	83 (6.2)	605 (45.2)	651 (48.6)	1339
1977–2008	12 (2.4)	270 (52.4)	234 (45.3)	516

Figures are expressed in terra grammes (1 Tg = 10^{12} g)
Figures in parentheses are per cent of total C stock

million tonnes of C were sequestered by farm forestry plantations in Uttar Pradesh (Dogra and Chauhan 2016). The potential of long-rotation species is higher, yet the potential of poplar and eucalyptus plantations at short rotation is substantial (Fig. 1).

In China, Guo et al. (2014) reported that total TOF biomass C stock increased by 62.7% from 1977 to 2008 (Table 7).

6 TOF Inventory

TOF needs to be assessed because of its production role and ecological functions and moreover for sustainable natural resource management (Singh and Chand 2012; Pujar et al. 2014). Information about TOF is felt necessary now for monitoring landscapes to formulate mitigation and adaptation strategies (Plieninger 2011; Schnell 2015) like in international agreements (UNCCD 1994; SCBD 2005; UNFCCC 2008). TOF inventories nationally will be helpful to design and formulate policies and legislation for its conservation and use. Locally such inventories will aid in management for its sustainable utilization and conservation of local forest (Schnell 2015). TOF inventories will be helpful for managing social, economic and ecological benefits in tropical countries (Guo et al. 2014) through planning and executing large-scale plantations outside forests. As of now, land-cover and land-use assessments and national forest inventories in some countries include biophysical and socioeconomic data of TOFs which can be used for monitoring and evaluating TOF.

Consequent of FAO's drive, many countries like India, Sweden, France, Switzerland, the USA, Great Britain and many more have included TOF in their National Forest Inventory (NFI) and National Forest Monitoring and Assessment (NFMA) (Barr and Gillespie 2000; Bélouard and Coulon 2002; Riemann 2003; Cumming et al. 2008; Brändli 2010; FAO 2012; Lister et al. 2012; de Foresta et al. 2013; Fridman et al. 2014; Tewari et al. 2014; Meena et al. 2017). Including TOF in the NFIs have clearly accounted huge amount of wood resources that otherwise remained unaccounted when TOFs were not included in the monitoring systems (Nowak 2002; Riemann 2003; Cumming et al. 2007; Nowak et al. 2008; Lister et al. 2012; Schnell et al. 2015). It was reported that in India, more than a quarter of growing stock of trees are from outside forests (Ahmed 2008; Pandey 2008; FSI 2011). Unfortunately, till date all kinds of TOFs are not included in NFIs and even not floated in public domain (de Foresta et al. 2013). Forest inventories do not often include TOF, and involvement of multi-stakeholders across sectors like agricultural, forest and urban is a major problem for monitoring TOF (Perry et al. 2009; de Foresta et al. 2013). Only two inventory systems, i.e. NFMA of the FAO (FAO 2012) and the Indian NFI (Tewari et al. 2014), monitor all types of TOFs. NFMA inventory is worked out in a single-phased sampling of few large units distributed uniformly in the study area (Schnell 2015). In contrast, Indian inventory is worked out in two-phased sampling with districts as first sampling units and TOFs in second phase sampling (Tewari et al. 2014).

TOF area covering larger than 1 ha area is captured by the resources survey satellite used for forest-cover assessment in present methodology, and area less than 1 ha is not (Dogra and Chauhan 2016). Thus, trees included in the tree cover constitute only a part of TOF, albeit a large part. Remote sensing can also be employed for TOF monitoring (Baffetta et al. 2011; Gregoire et al. 2011; Lam et al. 2011; Ståhl et al. 2011; Tewari et al. 2014; Schnell 2015), for example, coarse, medium and high spatial resolution (Foschi and Smith 1997; Lee and Lathrop 2005; Small and Lu 2006; Thornton et al. 2006, 2007; Walker and Briggs 2007; Walton 2008; Perry et al. 2009; Tansey et al. 2009; Fehrmann et al. 2014; Pujar et al. 2014; Schumacher and Nord-Larsen 2014; Zomer et al. 2014; Dadhich and Meena 2014). These remote sensing studies found out that traditional forest inventories underestimated in accounting the tree resources and established that globally in 43% farm land is covered with more than 10% tree canopy. TOFs are monitored simply with both unsupervised and supervised classification methods (Kumar et al. 2008) along with image-derived metrics for C stocks (Myeong et al. 2006). Some studies also used manual image interpretation based on only sampling (Hansen 1985; Fensham and Fairfax 2003; Fehrmann et al. 2014). TOF can remotely be studied on object-based classification also with 80–90% accuracies as metropolitan regions (Walker and Briggs 2007; Ouma and Tateishi 2008; Taubenbock et al. 2010), agricultural landscapes (Sheeren et al. 2009; Tansey et al. 2009; Liknes et al. 2010), scattered landscapes, suburban areas (Zhou and Troy 2008) and savannahs (Boggs 2010). In addition, active remote sensing technique like ALS was also employed to monitor TOFs (Rutzinger et al. 2008; Straub et al. 2008; Eysn et al. 2012). LiDAR data was reported effective to develop models for estimating TOF volume and biomass (Lefsky and McHale 2008).

TOF biomass and C models were also developed using allometric equations. These models however were not used very widely (Chave et al. 2005; Zhou et al. 2007, 2014; Nilsson 2008; McHale et al. 2009; Kuyah et al. 2012; Yoon et al. 2013). It was reported that allometry of trees and specific gravity of wood in the same species vary for TOFs and forest trees (Zhou et al. 2011). Specific gravity of TOF is higher in highly tapered trunk woods with more biomass allocated to crown than forest trees of same species. Moreover, TOFs are shorter than forest trees of same species (Harja et al. 2012). This is because these trees are more exposed to solar radiation, wind and agricultural residuals. Bamboo and palms are included in TOFs as they contribute substantially to national biomass stock; some crude estimation methods like Brown (1997) was used (Schnell 2015).

7 Livelihood Importance

Interaction of climate with farming practices and society has developed many tree-based farming practices (Gibbon and Schultz 1989; Gilmour and Nurse 1991; Kharal and Oli 2008; Painkra et al. 2016). Many trees and shrubs with multiuses are grown or allowed to grow in and around homesteads, farmland and other land uses. These trees are socially and culturally associated and hence, considered as integral component of livelihoods especially for rural areas in terms of food, medicines, fodder, timber, constructions, domestic energy and source of income along with maintaining ecological health (Regmi and Garforth 2010; Sayer et al. 2013; Sihag et al. 2015; Painkra et al. 2016). Trees on farmland are an integral part of the farming system and has the potential to meet the need of growing population by sustaining crop agriculture and livestock, production of commodities for exchange and as a form of energy and diverse tree products for sustaining rural livelihoods through income generation (Chakravarty et al. 2017a, b). Traditional Nepalese alder (*Alnus nepalensis*)-based agroforestry system with large cardamom crop is most suitable and offers comparative advantage over other livelihood options in Sikkim Himalayas where farmers are earning about one lakh rupees INR/ha/yr which is double remunerative than popular maize-potato cultivation, also providing much needed fodder and fire wood to the households along with other environmental services like resource conservation (Avasthe et al. 2011; Meena and Yadav 2014).

TOFs satisfy over two-thirds of the domestic energy demand in the Asia-Pacific countries in form of firewood and charcoal (FAO 2001b). TOFs are also known as 'trees that nourish' as poor and landless people derive essential products from them (Halavatau 1995) and are planted in African and Asian countries for producing food and other non-wood forest products. In Africa, Asia and Latin America, these trees are source of savings for the future in terms of their timber value, thus a sort of piggybank (FAO 2001b; Negreros-Castillo and Mize 2002). In these countries TOFs satisfy about 80% of the needs of the wood-based industries (Chave et al. 2004) generating income for the people. Trees and tree-based products provide jobs and products as well (Biswas 2006). Trees contribute towards sustainable livelihoods of rural poor but also have a special ethical role for Indians (Pandey 2007). TOFs are also an important source of feed for livestock in tropical countries, thus ensuring livelihood for the many who are primarily relying on animal husbandry for their well-being. In the Sudano-Sahelian Africa, three-fourths of 10,000 TOFs species in agricultural land use satisfies half of the fodder need of the livestock (FAO 2001b).

8 Problems of Growing TOFs

Many constraints are reported to slow down the growth and development of TOFs especially the farm and agroforestry to its full potential (Dogra and Chauhan 2016). These are:

- Long gestation period and market uncertainties.
- Not supported by financial institutions and extension services.
- No regulated markets.
- Unavailable improved planting material.
- Limited choice of profitable planting models.
- No separate laws and regulations for TOFs, guided by Forest Act.
- No regulated price mechanism.
- Unfavourable export and import policy.
- Trees on farm may compete with food crops for space, sunlight, moisture and nutrient reducing yield and can damage crops during its harvesting.
- Trees are host to insects and birds.
- Allelopathic effect by trees (eucalyptus) on crops.
- Rapid regeneration may take over the entire land like raimuniya (*Lantana camara*) and subabul.
- Labour intensive which may sometime cause scarcity in farm activities.
- Longer gestation period to realize income.
- TOFs may compete with crops especially where land is scarce.

9 Conclusion

TOF can be pivotal for balancing earth's CO_2 by fixing the C in its biomass and mitigate climate change. These plantations improve the microclimate and act as a valuable vegetation C pool and plant biodiversity centres. There are many species in TOF which give its inputs in mitigating environmental pollution, checking dust flow and noise pollution and helping to reduce atmospheric CO_2 and provide benefits to global climate. TOF is a remedial measure and alternative opportunity for controlling the present level of atmospheric CO_2 through increasing afforestation, preventing biodiversity loss and maintaining the bio-resources and ecological balance. TOF can be very helpful to bring back harmony to urban environment by providing ecosystem services. In recognizing the magnitude of the TOF resources, efficient inventorying is vital to formulate suitable national policy for its sustainable management.

10 Recommendations and Future Research

TOFs can efficiently fix atmospheric CO_2 in its woody biomass and fulfil the timber demands but need to be managed and monitored properly for which local, regional or national inventory is required. TOF is becoming a part of existing national forest inventory systems. Only the Indian and FAO inventories are including trees growing in all land uses. However, harmonization in analysing and reporting is still not advanced like in forestry sector creating difficulties locating the results from TOF assessments. Efforts are also needed by other countries to include all types of tree in their national inventories. Specific allometric biomass models need to be formulated and developed for the TOFs as uncertainties exist while applying forest-specific models. If forest models are to be used, they should be assessed for adequacy and validity. Terrestrial laser scanning effectively estimates tree volume without cutting or uprooting the tree, thus reducing manual work. Remote sensing is an effective tool in vegetation analysis though remotely sensed data is also an effective method to monitor and assist field inventories. However, more research is required to study model-assisted estimation and spatially balanced sampling methods for effective TOF inventories (Schnell 2015). Reconstruction techniques that verify the applicability of summary statistics for describing TOFs should be efficiently developed to generate artificial tree populations with varied spatial properties (Schnell 2015). TOF sampling simulation will use wall-to-wall remotely sensed data like two-phase sampling strategies.

The depletion of forest resources and increasing demands for forest products especially by the forest-dependent rural people have widened the gap between demand and supply in developing countries of the tropical world. This has warranted finding alternative options that will increase the supply of forest products to support rural livelihoods which now has become a fundamental concern for policymakers and planners. TOFs can be a forerunner as an alternative option for rural livelihoods and biodiversity conservation. Several national government policies which emphasize the need to initiate TOF in form of community and agroforestry programmes have empowered the NGOs to play a pivotal role in its popularizing for addressing the livelihood needs of poor households (Chakravarty et al. 2017a, b). Most of the households in rural tropics are not self-sufficient in food production as most of them either are landless or small and marginal land holders. The practice of growing TOFs as agroforestry on these small land holdings or village commons can serve as a source of food and some cash. Trees on farmland can also contribute towards the subsistence needs of the households in terms of fuel wood, fodder, fruits/food and local medicine and sometime hard-earned cash by selling the excess left after their use. Strengthening of self-help groups especially the women's savings groups in parallel with the development of TOFs programme may ensure a sustainable source of funds for group members' income-generating activities. Converting women farmer groups into savings and credit cooperative can represent the common interests of a larger proportion and can be a means to market TOF products in an organized way. Such institutions not only increase income but also strengthen the group capacity to mobilize community resources.

Forests in India cannot fulfil the timber and industrial needs on a sustainable basis due to insufficient growing stock, poor growth rates, inadequate financial and technical inputs and serious biotic pressures. The TOFs have to supplement the demand but need support from institutional research. A way forward lies in improving productivity of degraded forests and encouraging farm and agroforestry by encouraging and ensuring more and more TOF plantation through quality planting material. TOF in general and agroforestry in particular is a viable option for C sequestration and subsequent C trading, under the clean development mechanism (CDM). Potential of TOF under CDM can be increased with improved clonal seedlings, and area under it can be extended without affecting agricultural production. Availability of superior planting materials of eucalyptus, gamhar, maharukh and bakain under TOF in general and agroforestry in particular will substitute pulp-producing species, thus making TOF a viable CDM option. In addition, Dogra and Chauhan (2016) enlisted the following issues which need to be addressed on priority:

- Strengthening tree-based and farm forestry research and extension, i.e. increased support to R&D projects
- Strengthening extension and financial support system including digital support
- Nursery registration and certification to facilitate availability of quality planting stock
- Formalizing stakeholders
- Friendly harvest and transit laws and regulations for TOFs
- Agro-based status to wood-/timber-based cottage industries on value addition

Climate change places new and more challenging demands on maintaining sustainability requiring investments for enhancing research to offset the negative effects of climate change. Thus, partnerships with other national systems and international centres along with investment in laboratory scientists and infrastructure are needed.

Strong extension linkages among the stakeholders is essential for transferring technology, facilitating interaction, building capacity among farmers and encouraging farmers to form their own networks. This requires strengthening the global efforts for collecting and disseminating spatial data on tree resources through remote sensing. Statistical programmes should be also increased and encouraged through funding. International development agencies and national governments should encourage and support community participation in plantation programme planning and execution through technical, financial and capacity-building of local communities.

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Short-Rotation Forestry: Implications for Carbon Sequestration in Mitigating Climate Change

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Abstract

The unceasing loss of natural forest ecosystems and pressure on limited biomass production for fuel and timber has led to a search for a new platform. During the past few decades, plantation forestry has expanded around the world to meet the demands of biomass production, especially for energy consumption, with the aim to replace fossil fuels. In this context, short-rotation forestry (SRF; or fast-growing tree plantations) has played a major role due to its rapid growth. The potential of forest ecosystems to mitigate climate change has been the focus of many international organizations. However, to adapt and mitigate climate change, the potentialities of SRF need to be addressed: the majority of SRF is used for energy production, thereby releasing carbon dioxide (CO_2) to the atmosphere; thus, the conversion into durable products is urgently required. The carbon sequestration (C_{seq}) potential of different short-rotation plantations around the world has been assessed by different researchers to be 1.3–8.0 Mg C/ha/year. Similarly, studies have observed that carbon content in the soil tends to change with the establishment of SRF; most of the studies showed a declining trend of soil organic carbon, with a maximum of 20% in the initial years and followed by improvement of soil carbon up to 57%. However, the impacts of SRF on soil sustainability and biodiversity are another limitation on the acceptability of SRF in terms of its long-term sustainability. The proper management and implementation of policy incentives to maximize the importance of carbon credits could increase the sustainability of SRF and be considered as a future approach to mitigate climate change. Other afforestation and reforestation activities on wasteland, unproductive arable land, and agroforestry could also widen the scope of SRF to curb such climate change issues.

Keywords

Short-rotation forestry · Carbon sequestration · Climate change

Abbreviations

C	Carbon
CDM	Clean development mechanism
CO_2	Carbon dioxide
C_{seq}	Carbon sequestration
GHG	Greenhouse gas
MAI	Mean annual increment
SOC	Soil organic carbon
SRF	Short-rotation forestry
SRP	Short-rotation plantation

1 Introduction

In short-rotation forestry (SRF), fast-growing forest tree species are cultivated at a high density, with the aim of producing high biomass and growth within the shortest possible time span. SRF has been defined as the growth of high-density, fast-growing tree species plantations with the primary objective of producing high woody biomass (Christersson 2005). The tree species grown in SRF attain an exploitable diameter within 5–15 years (short rotation), whereas conventional tree species reach this diameter after 60 years or more (Hanson 1991). Fast-growing tree species produce a mean annual increment (MAI) of at least 15 m^3 per ha per year or attain a height increment of at least 60 cm per year (Dwivedi 1993; Cossalter and Pye-Smith 2003).

SRF aims to overcome the escalating industrial demands of commercially important wood species in the pulp, paper, furniture, and transportation sectors, among others, as quickly as possible. Biomass is the fourth largest energy source in world and contributes 14% of the energy to the total energy sector (Rockwood et al. 2004). In industrialized countries, 3% of the total energy consumed comes from fuel wood (Hall et al. 1999); in developing countries, 86% of the total wood consumed is used for fuel (WEC 1999). Nowadays, many countries are facing shortages of wood and wood-based resources because of the severe deforestation that occurred with the advent of industrialization, human development, and ever-increasing human populations (Jhariya and Yadav 2018). A major challenge for most developing countries is the shortage of fuel wood, whereas woody raw material for forest-based industries is a major concern in developed countries. Therefore, industrialized countries have started using modern biomass energy systems; however, in developing countries with very low incomes, people still have to depend on wood as fuel (Rockwood et al. 2004).

In 2016, global trade was 125 million m^3 for industrial round wood, 144 million m^3 for sawn wood, 87 million m^3 for wood-based panels, and approximately 109 million tons for paper and paper board (FAO 2016). This trade is expected to grow 5–8% every year from ever-increasing demands. Thus, the promotion of SRF on wastelands and community lands will pave the way for meeting the raw material demands of forest-based industries and for fuel wood, as well as help to preserve our forests from overexploitation (Pathak et al. 1981; Christersson 2005; Meena et al. 2016; Raj et al. 2018a, b). SRF is intended to optimize resource use efficiency in an environmentally safe and economically sound manner (Landsberg et al. 1997). Ultimately, SRF may substitute for the deforestation of tropical forests and temperate forests and would promote the conservation of forest resources required for mitigation of climate change and human health.

To establish SRF, a high density of genetically improved, locally adapted, and clonally propagated planting materials are deployed (Tuskan 1998). These plantations are established after extensive site preparation with adequate nutrient and fertilizer doses, along with intense weed control and pest management (Tuskan 1998). The growth increments of SRF vary by site quality, species selection, and intensity of management, but range from 6 to 21 Mg/ha/year dry matter in non-irrigated plantations and up to 30 Mg/ha/year dry matter in irrigated land (Wright and Tuskan 1997). Once the SRF crop matures, it is harvested and allowed to regenerate from coppice or replaced by using cuttings of new seedlings.

Because wood is a renewable source of energy, it can be easily substituted for other fuels (Segrest et al. 2001). SRF is considered to be carbon-neutral, indicating that it does not increase carbon dioxide (CO_2) in the atmosphere but helps in carbon sequestration (C_{seq}) (Tuskan and Walsh 2001). More than 100 species have been identified as SRF species (El Bassam 1998). In India, the recommended SRF for various agro-climatic regions include *Acacia* species such as *Acacia auriculiformis* (Earleaf acacia), *Acacia nilotica* (Babool), *Acacia catechu* (Khair), and *Acacia mangium* (Mangium); *Albizia* species such as *Albizia lebbeck* (Black siris) *and Albizia procera* (White siris); *Parkinsonia aculeate* (Jerusalem thorn), *Azadirachta indica* (Neem), *Ailanthus excelsa* (Indian heaven tree), *Casuarina equisetifolia* (Beech oak), *Eucalyptus camaldudensis* (Longbeak eucalyptus), *Leucaena leucocephala* (Subabool), *Melia azedarach* (Bakain), *Prosopis cineraria* (Khejri), *Prosopis juliflora* (Kikar), *Terminalia arjuna* (Arjun), *Populus deltoides* (Poplar), *Robinia pseudoacacia* (Black locust), and *Salix* species (Willow) (Rockwood et al. 2004).

The total growing stock in the Indian forest is 5822.377 Million m^3, and the MAI of 0.7 m^3/ha is far lower than the global average MAI value (2.1 m^3/ha). Imports of wood are increasing every year, from \$630 million in 2003 to \$2.7 billion in 2013 in India (FAO 2016). The total import of wood and wood-based products constituted of 328.2 billion Indian rupees in 2016–2017 (https://www.statista.com/statistics/625460/import-value-of-wood-india/) (Fig. 1).

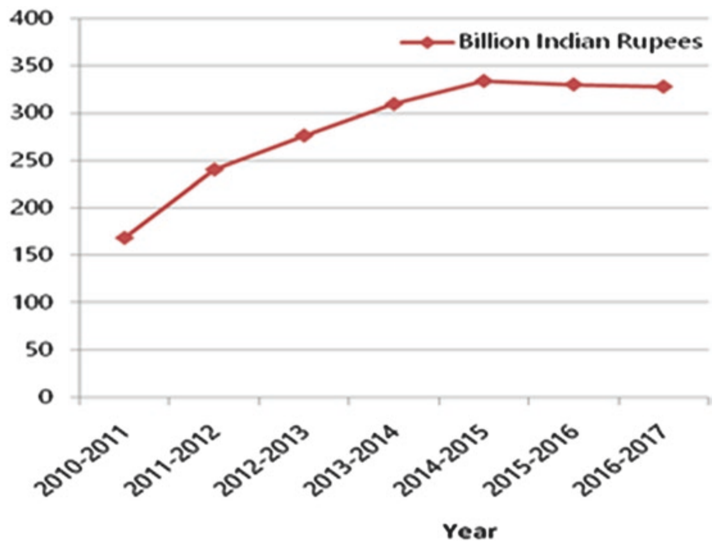

Fig. 1 The increasing import value of wood and wood-based products in India. (Data sourced from: https://www.statista.com/statistics/625460/import-value-of-wood-india/)

In this scenario, the increasing demand for raw material to be used in pulp, paper, furniture, and wood-based industries in India has led to the increased import of raw material; however, this is not a sustainable solution. Indian forests are not sufficient enough to fulfill the increasing demand for wood-based raw materials. In addition to the degraded conditions of forests, low growing stock, poor increments, less technological inputs, and excessive human pressures due to population explosions, industrialization, and urbanization, we cannot impose more pressure on these precious forest resources required for human survival; instead, conservation is required (Lal 2010; Jhariya 2014; Verma et al. 2015). Therefore, to bridge the gap between the demand for wood as a raw material and its supply, fast-growing and genetically superior SRF species are attracting attention. Many industries, such as the Western India Match Company Limited, ITC India Limited, West Coast Paper Mill Ltd., Tamil Nadu Newsprint and Papers Limited, Ballarpur Industries Limited, and Bharatiya Agro Industries Foundation, have started growing SRF species to meet their raw material requirement (Chauhan et al. 2017a).

This chapter explores the scope and potential of SRF with respect to biomass production, as well as the role of policy and other related incentives available to different land users in general. More specifically, climate change mitigation and adaption approaches through SRF, the dimensions on C_{seq} potential, ecosystem sustainability, soil, and biodiversity, etc. will be discussed in this chapter. Overall, this chapter attempts to expand the potentialities of SRF while challenging the climate change effects and considering future implications on a positive note.

2 Extent of SRF

SRF plantations are now a major source of raw material for wood-based industries in India and other countries. Most SRF in India includes poplar, eucalyptus, and beech oak (Chaturvedi 1998; Christersson and Verma 2006). Earleaf acacia is a species grown in humid tropical regions of northeast India, which has been reported to give higher pulp and fodder yield at 4-year rotations. *Tectona grandis* (teak), *Gmelina arborea* (gamhar), beech oak, mangium, poplar, willow, *Eucalyptus tereticornis* (forest red gum), subabool, and *Melia composita* (Hill neem) SRF have been used in the pulp and paper industries in the tropical plains, southern, and northeast humid tropics of India (Christersson and Verma 2006).

Species such as subabool, bakain, eucalyptus, and poplar hybrids are extensively raised in subtropical foothills of India (Christersson and Verma 2006). In temperate and sub-temperate regions, SRF includes planting black locust, *Acacia mollissima* (black wattle), and *Morus alba* (white mulberry) (Christersson and Verma 2006). In the semi-arid and arid regions of India, kikar and babool are planted. The Indian heaven tree, *Anthocephalus cadamba* (kadam), is also being promoted in India as an SRF species, especially in northern India. According to India's country report (2016), approximately 317,800 ha in India are estimated to be covered by poplar. Eucalyptus was introduced in India in the later part of the eighteenth century; it is currently estimated to be grown on more than 3 million

Table 1 Area, productivity, and rotation age of commercially important SRF species (Cossalter and Pye-Smith 2003)

Species (area)	Main countries raising these species	Rotation age (years)	MAI m^3/ha/year
Eucalyptus grandis (flooded gum) and *Eucalyptus hybrids* (3.7 Mha)	Brazil, India, South Africa, Uruguay, Congo, and Zimbabwe	5–15	15–20
Eucalyptus species (Tropical region) (1.55 Mha)	Vietnam, Myanmar, Madagascar, China, India, and Thailand	5–10	10–20
Eucalyptus species (Temperate region) (1.90 Mha)	Uruguay, Chile, Portugal, Spain, Australia, South Africa, and Argentina	10–15	5–18
Acacia species (1.40 Mha)	China, Indonesia, Malaysia, Vietnam, India, Philippines, and Thailand	7–10	15–30
Gmelina arborea (Gamhar) (0.1 Mha)	Costa Rica, India, Malaysia, and Solomon Islands	12–20	12–35
Poplar species (0.9 Mha)	India, China, USA, Europe, and Turkey	7–15	11–30

hectares, 80% of which is under agroforestry. India also has about 10% of the world's eucalyptus plantations (http://www.tnpl.com/web_pdf_files/Socio-Economic-and-Environmental-Impact.pdf).

Most SRF species are raised on farms and other non-forestry land. The government is focusing on raising SRF in problematic areas and farms to meet demands for fuel, wood-based industries, and paper industries and to reduce pressure from natural forests. *Populus trichocarpa* (black cottonwood), poplar, and other exotic hybrids are grown in rotations up to 6–7 years in Canada and the United States (Steenackers 1990; Dickmann et al. 2001; Ram and Meena 2014), with annual production up to 20 tons per hectare (Heilman and Stettler 1985). Hybrids of aspen (*Populus tremula*) crossed with quaking aspen (*Populus tremuloides*) have been observed to produce 20 m^3 per hectare per year (Christersson and Verma 2006).

In the Philippines, gamhar and acacias are grown commercially for SRF (Diaz and Tandug 1999; Christersson and Verma 2006), whereas bamboo species and hybrid poplars are being cultivated in China as SRF. Currently, 4.6 million hectares of eucalyptus plantations exist in China, with 60–70% of these plantations being under short rotations of 5–7 years (Zhou et al. 2017; Ashoka et al. 2017). Some example of SRF plantations with their area, productivity, and rotation ages are presented in Table 1.

3 Importance and Scope of SRF

SRF can provide enormous benefits when grown on wasteland, agricultural land, marginal land, and roadsides. The main benefits include pollution control, C_{seq}, ecological restoration of degraded sites, overcoming the rising demands of wood-based industries for raw material, phyto-remediation of polluted and heavy metal loaded soils, and providing a renewable source of energy, particularly for bio-energy and bio-fuel. The high growth rate of SRF species leads to higher biomass production, make them amenable for all of the previously mentioned purposes. The high MAI attained by these SRF species provides early returns to farmers and high quantities of raw materials to industries. Therefore, SRF is win-win situation for both farmers and industries.

In Brazil, SRF hybrid species of *Eucalyptus grandis* (flooded gum) crossed with *Eucalyptus urophylla* (Timor mountain gum) have been reported to yield dry biomass of 10–12 tons/acre/year. Flooded gum trees have been observed to provide total green biomass of more than 30 tons (Stricker et al. 2000). Poplar generally produces dry biomass of 5 tons/acre/year (Mercker 2007). *Pinus taeda* (loblolly pine), a fast-growing pine species, is capable of producing an average of 4 dry tons/acre/year if grown up to a 20-year rotation (Mercker 2007). Poplars in short rotation periods of 6–8 years are capable of yielding about 20–25 m^3/ha/year (Saddler 2002). Poplar hybrids can provide a total aboveground yield up to 500 m^3/ha in a 12-year rotation (Saddler 2002). In India, subabool has been reported to produce 112 t/ha of biomass, whereas forest red gum produces 96 t/ha in and babool produces 52 t/ha (Singh and Toky 1995).

A short rotation of willow has been reported to yield 3–7 tons/acre/year of dry biomass (Mead 2005). *Liquidambar styraciflua* (American sweetgum) and *Platanus occidentalis* (American sycamore) plantations have been observed to produce dry biomass up to 1 and 2.3 tons/year on 7-year rotations, respectively (Davis and Trettin 2006). For fast-growing species such as gamhar under 6-year rotations, yields of hardwood ranged between 40 and 120 m^3/ha on poor-quality and good-quality sites, respectively (Agus et al. 2001). This indicates that good site quality is a prerequisite for achieving higher productivity with these SRF species.

For the reclamation of waterlogged areas in India, species utilized for SRF include eucalyptus, *Casuarina*, arjun, karanj (*Pongamia pinnata*), willow, siris, poplar, *Acacia, Prosopis* and *Syzygium cumini* (Jamun) (Pandey et al. 2015). Willow species have been used for the removal of heavy metals such as cadmium; the high evapo-transpiration rate of such species facilitates phyto-remediation. Moreover, using trees for remediation is cost-effective and also provides other benefits to people (Aronsson and Perttu 2001).

In the long term, SRF improves soil properties by enriching soil with nutrients, enhancing soil organic carbon (SOC), and improving soil biological activities. After planting willow and poplar species, the total organic carbon and total nitrogen content have been reported to reach 4.0 g per kg and 0.2 g per kg in 12 years on sandy soil. Higher dehydrogenase activity in soil along with decreases in bulk density and increases in soil porosity has been observed in SRF (Kahle et al. 2007; Meena et al. 2017).

In addition to higher growth rate, biomass production and the renewable nature of SRF have great potential to capture a huge amount of carbon (C) at a fast rate. High annual C_{seq} in eucalyptus plantations (130.98 tC/ha/year) and poplar (18.59 tC/ha/year) and mixed plantations (21.83 tC/ha/year) of these two species has been observed (Sarangle et al. 2018). Similarly, plantations of fast-growing tree species, such as Timor mountain gum tree and *Acacia crassicarpa* (northern wattle), were shown to accumulate more C in their biomass than other long-rotation plantations of the same age (Chen et al. 2015).

Economic returns are also high for fast-growing short-rotation species due to the huge biomass production for industries and other bioenergy and biofuel purposes. One study carried out in China found that net present values range from $1024 to $6925/ha, equivalent annual incomes range from $120 to $623 ha/year, and internal rates of return range from 13.2% to 29.3% for popular plantations (18,032 ha) (Wang et al. 2014). Similarly, plantations of forest red gum tree can produce 201.64 m^3/ha, which is equivalent to Rs.1210 432/ha after 8 years (Jalota and Sangha 2000). Therefore, SRF has the potential to provide high economic returns to farmers and other involved agencies.

There is lot of scope for SRF in India to meet demands for energy resources, biodiesel, and raw materials for wood-based industries. In addition, the high biomass production of SRF makes it a desirable option for mitigation and adaptation for climate change. Moreover, SRF has the capability to provide early returns to farmers, which therefore make it a good option for generating income in a short period of time. SRF can be used on wastelands for their reclamation and restoration, on agricultural land as boundary plantations, as part of agroforestry, and on village community land under joint forest management to improve a community's economic status (Singh et al. 2014; Raj and Jhariya 2016a, b, Raj et al. 2016).

4 Important SRF Species in India

In India, earleaf acacia, khair, mangium, babool, black siris, white siris, neem, Jerusalem thorn, Indian heaven tree, beech oak, longbeak eucalyptus, subabool, bakain, khejri, kikar, arjun, poplar, black locust, bamboo species, kadam, Gamhar, pink cedar (*Acrocarpus fraxinifolius*), and willow species are the most important SRF species (Rockwood et al. 2004). These species show high productivity and can be grown in the different soil types and agro-ecological zones of India (Tables 2, 3, and 4).

5 SRF for Higher Biomass Production

To meet the demands of the pulp, paper, furniture, packaging, veneer, and plywood industries, raising SRF tree species is an eco-friendly and viable solution (Martin and Nordh 2009). In many countries, such as Sweden, willows are commercially raised to meet energy demands. Tree species such as poplar, pine, birch (*Betula spp.*), and eucalyptus species are being used in China commercially to meet the demands of various wood-based industries (Chen et al. 2015). Now, the focus is on renewable energy sources that can meet demands sustainably without deteriorating the environment. Therefore, SRF is being promoted by various governmental and

Table 2 Important SRF species and their productivity

Species	Family	Productivity	References
Dalbergia sissoo	Fabaceae	9–15 m^3/ha/year (10-year rotation)	FAO (2001)
Acacia auriculiformis	Fabaceae	8–35 tons/ha/year (10-year rotation)	Schmerbeck and Naudiyal (2014a, b)
Acacia mangium	Fabaceae	46 m^3/ha/year (9 -ear rotation)	Patil et al. (2012)
Acacia nilotica	Fabaceae	3–4 m^3/ha/year	Mohapatra et al. (2005)
Albizzia lebbeck	Fabaceae	66 tons biomass (after fifth year)	Yadav (1986)
Casuarina equisetifolia	Casuarinaceae	11 m^3/ha/year (12- to 15-year rotation)	Ray (1971)
Eucalyptus camaldudensis	Myrtaceae	8–12m^3/ha/year (10- to 20-year rotation)	Mohapatra et al. (2005)
Leucaena leucocephala	Fabaceae	30–55 m^3/ha/year	FAO (2001)
Melia azedarach	Meliaceae	15–17 m^3 /ha/year (15-year rotation)	(http://www.worldagroforestry.org/sites/default/files/Timber%20demand%20supply-Northwest-No6.pdf)
Prosopis juliflora	Fabaceae	4.9–8.4 kg/tree/year	Chaturvedi et al. (1988)
Populus deltoides	Salicaceae	20–25 m^3/ha/year (8- to 10-year rotation)	Mohapatra et al. (2005)
Robinia pseudoacacia	Fabaceae	23 m^3/ha (at 10-year rotation age)	NAS (1983)
Salix viminalis (basket willow)	Salicaceae	20–30 tons of biomass (10–15 tons of seasoned wood) per hectare per year	Rajoriya et al. (2016)
Gmelina arborea	Verbenaceae	12 and 50 m^3/ha, MAI in 5–8 years	FAO (2001)
Anthocephalus cadamba	Rubiaceae	20 m^3/ha/year (at 9-year rotation	Krisnawati et al. (2011)

Table 3 SRF species suited for various soil types in India (Benwood 2011)

Species	Soil sites
Populus deltoides	Sandy to fine loam
Leucaena leucocephala	Variable soils
Melia composita	Fertile and sandy loam
Eucalyptus hybrids	Sandy loam, alluvial soils are preferred
Robinia pseudoacacia	Acidic soils and sloping land
Morus alba	Sandy loam to clay loam
Prosopis juliflora	Saline, sandy soils
Gmelina arborea	Sandy loam and deep soil
Ailanthus excelsa	Porous sandy loam
Casuarina equisetifolia	Red gravelly loam, coastal and saline soils
Terminalia arjuna	Moist locations and sandy loam soils
Tectona grandis	Deep black soil, black clay and black loamy soils

Table 4 Zonewise distribution of various SRF species in India (Benwood 2011)

Species	Distribution
Acacia auriculiformis	Humid tropical regions in the north
Acacia mangium	Eastern India and the humid tropics
Acacia mollissima	Southern India
Populus deltoides	Irrigated agro-ecosystem in northwestern states
Leucaena leucocephala	Throughout the country
Eucalyptus hybrid	Throughout the country
Robinia pseudoacia	Temperate northwestern Himalayas
Morus spp.	Temperate northwestern Himalayas
Prosopis juliflora	Arid and semi-arid areas
Gmelina arborea	Northeastern humid tropics
Bamboo species	Throughout the country, with most species in the northeastern states
Anthocephalus cadamba	Northeast regions and southern states of India
Ailanthus excelsa	Central India, arid regions, and northern part of peninsular India
Casuarina equisetifolia	Coastal areas and salt-affected soils
Terminalia arjuna	Lower Himalayan tracts and eastern India
Cryptomeria japonica	East Himalayas and humid regions

non-governmental agencies as a solution for meeting demands for wood products and combating climate change.

SRF species are high above-ground biomass (18–50 t/ha), which makes them suitable for bridging the gap between the demand for and supply of wood. In India, 90% of industrial round wood demand is met from fast-growing species outside forests. *Populus* spp., *Eucalyptus* spp., *Acacia* spp., subabool, *Melia dubia* (Malabar neem), willow, and beech oak are being promoted in India and are gaining the interest of farmers and industries. When grown at high density, these SRF species can provide farmers with high returns.

Sachs and Low (1983) reported 22 oven-dry tons of biomass/ha/year under a 6-month rotation in a flooded gum tree plantation at very high density (17,200 trees/ha). Two years after planting *Eucalyptus camaldulensis* (river red gum) at 5000 trees per acre, the plantation yielded 16 dry tons of biomass per acre per year.

With 9-year-old poplar, the total biomass (above-ground and below-ground) varied from 71.50 tons/ha to 251.50 tons/ha, depending upon plant density (Puri et al. 1994). For multipurpose bio-energy crops such as arjun (41.62 tons/ha), neem (19.22 tons/ha), kikar (56.50 tons/ha), karanj (26.60 tons/ha), Beech oak (42.10 tons/ha), South American mesquite (27.75 tons/ha), babool (50.75 tons/ha), forest red gum (31.77 tons/ha), *Pithecellobium dulce* (32.25 tons/ha), and *Cassia siamea* (kassod) (21.65 tons/ha), high biomass production has been observed (Singh et al. 2010). For 1-year-old seedlings of some fast-growing species, such as *Samanea saman* (40.07 tons/ha/year), *Erythrina variegata* (32.02 tons/ha/year), *L. leucocephala* K-8 variety (45.52 tons/ha/year), and black siris (27.40 tons/ha/year) high biomass was recorded, which indicates their suitability as high biomass production species (Ponnamal and Gnanam 1988).

During a study on the biomass production potential of four SRF species on a 4-year rotation, *Betula pendula* (silver birch) was observed to produce high dry biomass up to 3.3 tons/ha/year, *Acer pseudoplatanus* produced dry biomass of 1.2 tons/ha/year, populous hybrid *P. trichocarpa* × *P. deltoides* produced dry biomass of 4.2 tons/ha/year, and *Salix viminalis* (basket willow) produced 3.5 t of dry biomass ha/year (Walle et al. 2007).

In a hybrid of *E. torelliana* × *E. citriodora*, hybrid vigor and high standing volume production was reported at the rotation ages of 7, 10, and 23 years. Standing volumes of 0.18 m^3, 0.53 m^3, and 3.03 m^3 and yields of 16.17 m^3/ha/year, 33.12 m^3/ha/year, and 82.79 m^3/ha/year were observed at 7-, 10-, and 23-year rotations, respectively (Kumar et al. 2010). *Eucalyptus* plantations have been reported to produce pulp up to 5.9–10.9 t/ha/year (Fenton and Romero 1995; Bertolucci et al. 1995). Forest red gum and beech oak have been reported to produce 20 times more at high densities of 40,000 plants per hectare (Rai and Srinivasan 2012).

In SRF with willow coppice in Kashmir, a higher fresh biomass yield of 15.55 tons/ha/year was obtained after 4 years of plantation, which increased to 23.41 tons/ha/year after 3 years when willow coppice was grown a second time (Masoodi et al. 2014; Yadav et al. 2017b). Thus, SRF can yield high biomass, thereby meeting the demands of wood-based industries.

6 Economic Importance of SRF

SRF is an ecologically and economically viable option for meeting the demands of wood-based industries, reducing pressure on forests, and providing higher and early returns to farmers in comparison to commercial forestry. However, farmers may be reluctant to adopt SRF because of the long gestation period of trees in comparison to food crops, a lack of availability of planting materials, a lack of market intelligence about demand and supply of wood-based products, and mostly because the small size of land holdings. However, SRF is profitable for both farmers and wood-based firms because it provides high returns. The crops grown will of superior genotypes; therefore, uniform growth rates and quality are achieved. Many paper, pulp, and wood-based industries of India, such as Western India Match Company Limited, ITC India Limited, West Coast Paper Mill Ltd., Tamil Nadu Newsprint and Papers Limited, Ballarpur Industries Limited, and Bharatiya Agro Industries Foundation, are now also encouraging farmers to take up SRF to fulfill their demand for raw materials.

Chaudhary and Chaudhary (2012) planted 12,000 poplar trees of superior genotype at Chaudhary Farm in Pilibhit, Uttar Pradesh, India. After harvesting trees every 7 years, high yields of 1000 quintal of timber per acre have been obtained, along with economic returns of Rs. 100,065 per acre per year.

In poplar-based agroforestry, high net returns were reported for poplar and sugarcane intercropping (Rs. 64,355/ha/year) followed by poplar and turmeric intercropping (Rs. 59,543/ha/year) and poplar and rainfed wheat (Rs.18,719/ha/year). Poplar mono-cropping generated Rs. 20,188/ha/year, whereas a traditional rice-wheat-crop rotation could obtain Rs. 22,970/ha/year as the net income (Chahal et al. 2012). This underscores the hypothesis that two-tier cropping is more profitable than mono-cropping.

Chauhan et al. (2015) found high economic returns from poplar block plantation in comparison to boundary plantation and sole cropping of rice and wheat with a Benefit:Cost ratio of 3.30, 1.90, and 1.61, respectively. Beech oak intercropping at 4-year rotation with groundnut has been found profitable, with net annual returns of Rs. 88,827/ha/year in comparison to traditional rice cultivation returns of Rs. 68,381/ha/year (Saravanan and Vijayaraghvan 2014). Beech oak clonal propagation for poles and pulp gives a higher B:C ratio (3.88–5.05) than beech oak seedlings (1.66–1.91) (Saravanan and Vijayaraghvan 2014). Growing willow coppice in Kashmir valley at high density provided gross and net income after two-time cultivation of trees on the same land (4-year rotation) equivalent to ₹8,76,750 and ₹4,96,255 per hectare, with a net present worth of ₹2,00,663 and a B:C ratio of 1.73 at a discount rate of 12% (Masoodi et al. 2014).

Further promoting SRF on farmers' fields and community land under the Clean Development Mechanism (CDM) of the Kyoto Protocol can help farmers to earn revenues from the sale of carbon credits. As SRF has high biomass production capacity and 50% of the dry biomass is carbon, SRF has high C_{seq} potential. Such SRF projects can be taken up under CDM, and these carbon credits can be sold to developed countries to offset their carbon emission reduction targets. Therefore, SRF is economically viable because it provides quick and high returns; in addition, being renewable, it can serve as a permanent option for steady income streaams.

7 Policies and Initiatives Related to SRF

Over the last few decades, there has been universal concern over the inevitable effects of climate change, especially on vegetation ecosystems, due to the unavoidable phenomena of global warming and climate change. Climate change mitigation and adaptation activities through the adoption of tree-based systems have been considered as a holistic solution. The concept of using fast-growing tree species could prove a viable option to mitigating the challenge of climate change by a faster rate of biomass accumulation, thereby capturing CO_2 in the woody biomass as well as reducing the pressure on natural forests (Chauhan et al. 2017b). In addition, afforestation and reforestation activities would help to reclaim degraded land and wastelands by providing the services of C_{seq} on one side and conservation of land resources on the other side. Thus, the regulation of tree plantation activities by implementing proper plantation policies with the aim to improve the tree cover area should be given top priority. For example, in India, the National Forest Policy 1988 set up the goal to maintain 33% of the total geographical area as forest and tree cover area. In an attempt to increase the tree cover area in India, the government has taken initiatives and started programs such as the Green India Mission (2014) and National Agroforestry Policy (2014). In the context of SRF, the main purpose is for higher biomass production and replacement of fossil fuels. The National Biofuel Policy 2008 of India was one of the major steps taken by the government, and *Jatropha curcas* was one of the short-rotation tree species identified in this aspect (Basavaraj et al. 2012).

The government of Australia initiated the Carbon Credit Act 2011 with respect to plantation forestry, with the aim to reduce carbon emissions and benefit farmers by selling their carbon credits. Other policies with respect to plantation forestry have been implemented in various countries, but their norms and regulations vary by region and may be very rigid for farmers and other stakeholders. Therefore, governments and concerned authorities should review the regularization and user-friendliness of adopted policies. Other than the implementation of policy, some incentives can be provided to benefit land users directly or indirectly. Incentives such as the regulation of market prices, supply of planting material, exemption of taxes, and financial or loan support would be helpful to farmers, but the nature and amount of incentives provided vary from country to country. In this regard, Enters et al. (2004) highlighted the incentives required for the evolution of plantation in developed and developing countries. More incentives are required for developing countries at the initial phase of plantation development. The accessibility of incentives by different beneficiaries in developed countries is very promising and attractive in nature in comparison with developing countries.

Mola-Yudego and Pelkonen (2008) in Sweden reported that the implementation of policy incentives increased the farmers who adopted short-rotation willow plantation by 70% during 1986–1996. This proved that providing incentives to farmers not only encourages farmers to adopt SRP but also serves as a future strategy to achieve more biomass production. Lindegaard et al. (2016) also reported the importance of SRP policies for growers and emphasized that there is an urgent requirement to disseminate the information and educate the farmers and policymakers to impart the benefits derived from SRP. Governments and concerned authorities also need to provide financial support with the aim to implement the policies for the long term.

Enters (2004) studied the impact of policy and incentive availability with respect to plantation activities for different land users in the Asia-Pacific region. The author outlined three main stages during the process of plantation establishment: the initiation phase, acceleration phase, and final or maturation phase. The type of incentives to be provided depends on the developmental phase of the plantation. For example, direct incentives at the initiation phase of plantation will help to achieve successful plantation programs; later, direct incentives may be replaced by other kinds of incentives. It was also highlighted that the structure and function of social and political factors can affect the availability of incentives. Thus, the implementation of effective policy initiatives and other incentives will be helpful in stimulating the expansion of plantation forestry.

8 Impact of SRF on Soil Sustainability

Soil plays a crucial role in the overall growth and development of a plant. Nutrient reserves in the soil ecosystem provide support that has a pronounced effect on a plant's productivity. In other words, the level of soil fertility or the nutrient status of soil has a significant impact on plant growth and productivity. The sustainability of soil resources, which helps to fulfill the nutrient requirements from the soil system, needs to be critically examined. Furthermore, the self-sustainability of soil nutrient reserves is also required to be maintained or improved with every plantation activity (Jhariya et al. 2018; Kumar et al. 2018). Tree-based land use systems provide greater soil sustainability than do treeless or agricultural systems. In an agricultural system, different management activities, such as tillage, the application of fertilizers, and pesticides use, influence the nutrient status of the soil, especially SOC storage in the soil (Chen et al. 2004; Guo and Gifford 2002).

It is important to understand the nutrient status of the soil where afforestation or reforestation activities are planned. Afforestation and reforestation activities are expected to increase the soil organic C_{seq} potential of the site (Sauer et al. 2012). With the introduction of SRF in an area, there will be significant changes in the soil properties. Generally, SRF and fast-growing species plantations are established where the land is to be converted from arable land, abandoned land, wasteland, or degraded land. In a few cases, SRF is introduced where lands are covered by natural forests, pasture lands, or grasslands.

According to the previous land use pattern, the impact of SRP on soil properties may be negative or positive. In this regard, Guo and Gifford (2002) reported that the SOC stock of different land use systems changed according with the change in their previous land use pattern. They found that a 10% decrease of SOC when original pasture land was converted to plantation and more SOC loss (13% decrease) when native forest was shifted to plantation forestry. Interestingly, however, an increase of

Table 5 Soil carbon changes after introduction of SRP

Short-rotation forestry/plantation	Former land use pattern	Soil depth (cm)	Time span (years)	Change in soil carbon (%)	References
SRF poplar (Italy)	Agriculture (maize- wheat)	0–10	9–10	57% increase	Bene et al. (2011)
Poplar, aspen, and willow (Germany)	Arable land	10–30	7–9	15% decrease	Jug et al. (1999)
Hybrid aspen (Estonia)	Arable land	0–30	5–15	10.4% increase	Lutter et al. (2016)
Pinus radiata (New Zealand)	Pasture	5	5	16% decrease	Chirino et al. (2010)
Eucalyptus nitens (New Zealand)	Pasture	5	5	8% decrease	Chirino et al. (2010)
Cupressus macrocarpa (New Zealand)	Pasture	5	5	2% decrease	Chirino et al. (2010)
Cupressus lusitanica (Ethiopia)	Abandoned Farmland	10	20	25% increase	Poultouchidou (2012)
Eucalyptus saligna (Ethiopia)	Abandoned Farmland	10	20	20% increase	Poultouchidou (2012)
Poplar spp. (USA)	Agriculture	32	12	No change	Coleman et al. (2004)
Pinus radiata (Australia)		15	5	19–2.7% decrease	Smethurst and Nambiar (1990)
Meta-analysis (many species covered)	Agricultural land	< 10	5	3.46% decrease per year	Paul et al. (2002)

18% SOC occurred by the time the crop area was changed to a plantation. For the overall development of soil quality as well as for maintaining soil productivity, the role of soil organic matter is very critical; thus, it should be considered as a key parameter in deciding the soil quality (Teepe et al. 2003; Verma et al. 2010).

In general, during the early phases of plantation, SOC content seems to decline and then begins to build up with the passage of time. This may be due to more disturbances in the soil at early stages due to the tree establishment process, less litter fall accumulation, and a high mineralization rate (Paul et al. 2002; Jug et al. 1999; Makeschin 1994). Changes in soil C content after introduction of SRF and fast-growing tree species are presented in Table 5. It can be seen that there were more changes in soil C content when the arable land was changed to plantation; in addition, the soil C storage or accumulation seems to change along with species planted as well as the previous land use pattern. The response of different tree species growing in same environmental condition has the potential to create a varying C accreditation pattern in the soil. For example, Abate (2004) claimed that *Cupressus lusitanica* exerts a higher quantity of SOC than *Eucalyptus globulus* due to its higher production of litter mass and coarse roots. Litter fall and decomposition processes play a major role in the development of SOC in the plantation system; however, the rate of litter accumulation depends on species and climatic factors, among others. Due to differences in their litter fall patterns, the quality of litter and rate of decomposition will have a significant impact on the amount of C sequestered in the soil; this has proven to be species specific (Vanguelova and Pitman 2011; Jhariya 2017a, b).

In addition to SOC, other physical, chemical, and biological properties of soil are inclined to change after the establishment of SRP. For example, in Germany, Jug et al. (1999) observed reductions in the soil pH and cation exchange capacity of soil after the establishment of poplars and willow. Similarly, reductions in soil pH after the establishment of SRF in different locations in Europe were reported (Ritter et al. 2003; Uri et al. 2011; Lutter et al. 2015). However, Muys et al. (1992) had observed an increase in soil pH with the plantation of *Alnus glutinosa*, *Prunus avium*, *Fraxinus excelsior,* and *Tilia platyphyllos*. Change in the soil reaction can be determined by the action of the species planted with the adaptability of the site and could modify the soil nutrient dynamics with passage of time. Therefore, for sustainability of the SRP, an understanding of soil pH and its dynamics is very important because soil mineralization and other microbial activity have been affected by soil pH, which influences the overall soil nutrient cycling (Lutter et al. 2016; Jhariya 2014; Meena and Meena 2017).

The biological properties of soil in terms of microbial populations and their activity have also played a significant role in maintaining soil fertility and productivity. Like SOC, microbial activity in the soil decreases during the initial stages of plantation because there are more disturbances in the soil; however, in later phases, the microbial activity shows a significant increase (Minor et al. 2004). Improvements in soil ectomycorrhizal fungi in different plantations of species, such as willow and poplar, have been recorded in comparison with arable land (Baum et al. 2009; Rooney et al. 2009). Soil with a higher microbial biomass is expected to have higher SOC and is considered to be one of the early sensitive indicators of a soil system (Jenkinson et al. 2004). The amount and quality of litter added to the soil would preferably affect the rate of decomposition by influencing the activity of soil microbes. Generally, it is believed that soil microbial biomass tends to change with the shifting of land use patterns as the substrate availability and other growth favoring condition is frequently changed.

Mao and Zeng (2010) observed a change in soil microbial biomass C, with reductions during the early development of plantations and a tendency to increase with the passage of time. The positive impact of plantations on soil microbial biomass C is evident from the works of Kahle et al. (2010) and Pellegrino et al. (2011). SRF has been proven to improve soil biodiversity by increasing microbial populations and thus influencing the soil nutrient cycling. The effects of SRP in terms of soil sustainability can be determined by the maintenance of balance between the nutrient removal during harvesting and nutrients addition by fertilization (Vanguelova and Pitman 2011). During the harvesting period of the plantation, there will be heavy disturbances in the soil, with exports of nutrients from the soil. For example, O'Connell and Glove (1999) reported that more than 500 kg N/ha was removed from the soil of an 8-year-old *Eucalyptus globulus* plantation during harvesting. Therefore, for long-term soil sustainability under SRP, harvesting practices that lead to less disturbance in soil should be considered, in addition to leaving the leaf litter and other waste materials after harvesting (Ranger and Belgrand 1996).

9 Impact of SRF on Biodiversity

The constant loss of biodiversity due to human interference has resulted in a decrease in forest area as well as an increase of atmospheric CO_2 (Cairns and Meganck 1994; Gross 2016). Forests and other natural ecosystems have a strong linkage to building up biological diversity, which form a series of webs and maintain the overall stability of the terrestrial ecosystem. During the last two decades, people have started to realize the impact of losing biodiversity, compromising the services of the ecosystem with human satisfaction (Cardinale et al. 2012).

Deforestation, illicit felling, and burning inside forests have been done intentionally by humans while in search of their requirements for food, fodder, fuel wood, and timber, which has tremendous effect on forest biodiversity (Jhariya et al. 2012, 2014; Kittur et al. 2014a, b). In this regard, plantation forestry aims to reduce the pressure on limited natural forestry as well as serve the demands for tangible products derived from the forests. It is generally expected that undisturbed or natural forest ecosystems will have more biodiversity than plantation systems. Stephens and Wagner (2017) have argued that plantation forests have less biodiversity than natural forests, but higher diversity than agricultural or other land use systems. Similarly, Bremer and Farley (2010) claimed that the level of biodiversity in plantations may be higher when compared with agricultural land and degraded areas but lower than natural forests and grasslands; they also indicated that plantations consisting of native indigenous tree species will have more diversity than exotic plantations. Sustainable forest management aims toward long-term sustainability by conserving and maintaining the biological diversity of natural resources. Carnus et al. (2006) reported that plantation forestry can increase diversity while meeting the demands for fuel wood and timber; they also suggested that plantation forestry should be managed in such a way that the economic outlook is not the top priority but the diversity of the plantation is also considered.

It is apparent that the effects of plantations on biological diversity may be either positive or negative. For example, a negative or lower level of biodiversity in plantations was reported by various authors (Paritsis and Aizen 2008; Makino et al. 2007; Raman 2006). On the contrary, an increase in biodiversity inside plantations has been described in other reports (Tomasevic and Estades 2008; Stephens and Wagner 2017). It is obvious that the level of biodiversity is significantly influenced by management intensity (Braun et al. 2017; Carnus et al. 2006) and other factors such as land use history, management practices, and species planted (Bremer and Farhey 2010; Carnus et al. 2006).

The influence of SRF on the level of biodiversity will also have a significant impact, as general plantation forestry does. In this regard, few studies have been

Table 6 Possible SRF influences on biodiversity

Category of species	Level of biodiversity	Possible impact
Plant vegetation	Medium to good	Initial decrease in plant species richness followed by an increase in species richness over a course of time when the initial disturbances are stabilized followed by appropriate management practices
Arthropods	Medium	Possible loss of arthropod population when a native species is replaced by an exotic species; the selection of species would significantly influence arthropod diversity and species produced; flowering before harvesting would help with arthropod diversity. Potential to increase the biodiversity of arthropods whenever mixed species plantations are established
Bird	Medium	Bird populations in the plantation would be dependent upon the plantation stand dynamics. Comparable increase in bird populations when plantations are established adjacent to agricultural lands or former arable lands.
Mammals	Medium	Plantation stand dynamics also influence on the population of mammals. Prey-predator relationships inside the plantation also signify the biodiversity level in the plantation.

carried out and thus little information is available. In general, SRF is mainly composed of homogenous or single species, unlike a natural forest, thus creating low species richness. In other words, only the species that is favored by a plantation may persist and others may be lost. Hardcastle et al. (2006) attempted to determine the possible impact of SRF on biodiversity status, as shown in Table 6.

10 SRF and Climate Change

With the increasing impact of climate change owing to increased greenhouse gas (GHG) emissions coupled with increasing demands for fuel, tree-based raw materials for various industries, and tree-based eco-friendly fuel, a sustainable solution is needed that can mitigate climate change, help in adapting the environment to climate change, and fulfill demands for fuel and wood-based raw material. SRF is one such eco-friendly option for fulfilling all of these objectives. SRF has high biomass production potential within a short period of time; therefore, SRF can sequester more C at faster rate than conventional forestry. A major cause of pollution and GHG emissions is the use of fossil fuels for producing energy; fossil fuels have negative impacts on the environment and are also non-renewable resources. Moreover, the availability of fossil fuels will decrease in near future (Eduardo et al. 2017). Thus, shifting to a renewable, eco-friendly source of energy that can mitigate energy demand is required. SRF is the best option because bio-energy from biomass is known to reduce GHG emissions along with being a sustainable supply of energy (British Forestry Commission 2007).

Zurbaa and Matschullata (2015) compared SRF (willow- and poplar-based) with rapeseed cultivation as energy sources and studied the ratio between soil respiration and combustion heat released (per hectare) from products of rapeseed, willow, and poplars. Poplar and willow SRF showed low ratios. Therefore, such species can be promoted as a source of energy for meeting energy demands. Further studies must be carried out to evaluate the suitability of various SRF species for energy production. High biomass production of 18–50 t/ha has been reported in SRF species, which makes them suitable for bridging the gap between demand and supply of wood. *Populus* spp., *Eucalyptus* spp., *Acacia* spp., subabool, Malabar neem, willow, beech oak, arjun, neem, *Erythrina variegata*, karanj, *Prosopis alba* (South American mesquite), kassod, black siris, silver birch, and basket willow have been observed to produce high biomass and therefore can meet escalating energy demands in an eco-friendly manner (Sachs and Low 1983; Ponnamal and Gnanam 1988; Walle et al. 2007; Rai and Srinivasan 2012; Dadhich et al. 2015).

Another benefit of SRF is that it can be integrated with traditional agroforestry practices, leading to crop diversification; in addition, SRF conserves soil, water, and biodiversity, thereby enhancing ecosystem resilience (Rowe et al. 2009). Additional priorities being given to fuels include more climate resilience, more production to bridge the gap between the demand and supply of fuels, and increased C_{seq} in comparison to conventional agriculture (Sims et al. 2006). SRF has been designated as a cost-effective way to improve resilience because the diversification of crops reduces pest and insect attacks and act as a habitat for various macroflora and microflora (Walker 1995); this biodiversity acts as a buffer against environmental variability because the response will be different due to greater diversity (Yachi and Loreau 1999; Elmqvist et al. 2003).

Because of the higher C_{seq} potential of SRF, it is the best option for mitigating climate change. The C_{seq} rate in SRF-based agroforestry system is higher than that of other species because it helps with above-ground and below-ground C_{seq} in trees and sequesters more C in soil. The mean C storage (t C/ha) in various tropical SRF (rotation age 3–20 years) species has been observed to range from 8 to 59 (t C/ha) (Schroeder 1992). In addition, an increase in SOC has been observed in most SRF-based land use systems. In this way, SRF is climate smart option for meeting energy and wood-based raw materials demand.

11 Carbon Sequestration Potential of SRF

The ever-increasing impact of climate change has fueled an imbalance in ecosystem productivity and sustainability. The issue of global warming with increases in atmospheric CO_2 and other GHG concentrations have become hot topics. There has been a considerable increase in CO_2 concentration, which is approximately 40% greater than in pre-industrial time (IPCC 2013) and still increasing. Uncontrollable human behavior and its related activities have created natural resource crises. In addition, the release of CO_2 contributes significantly to increased CO_2 concentrations in the atmosphere, which are expected to be approximately

1.2 PgC/year, or 12% of the total CO_2 emitted from anthropogenic sources (van der Werf et al. 2009; Yadav et al. 2017).

The alarming rise in CO_2 concentration during the past few decades requires a strategy to mitigate and adapt to the challenging climate change issues. The importance of forests and other natural vegetation in the conservation and sustainable use of natural resources has been realized. Even though the forest ecosystem represents only 30% of the world's geographical area (FAO 2006), it is contributing more than 75% of the C reservoir of the terrestrial ecosystem (Bolin and Sukumar 2000). The sustainable management of forest ecosystems could lead to more space for C storage in tree components, such as leaves, stems, and roots, as well as in the soil ecosystem. Unfortunately, the pace of deforestation and desertification is constantly increasing and becoming a major concern across the globe. Therefore, plantation forests have become a strategy to meet the multifarious demands of society, unleash pressure on the natural forest ecosystem, and mitigate the global atmospheric C budget (Cunningham et al. 2015).

Forests and other tree-based land use systems have extensive potential to capture atmospheric CO_2 and store ir in their biomass (above and below ground) as well as in the soil ecosystem. This strategy is considered to be a viable option toward the mitigation of climate change. However, the natural forest ecosystem has not been managed properly and the principles of sustainable forest management system are not executed most of the time. Plantation activities have been started across the world, with the main aim to produce higher biomass production for replacing fossil fuel. The United Nations Framework Convention on Climate Change (UNFCC 1998) reported that plantation forestry is a potential mitigation option for GHGs under the activities of afforestation, reforestation, and deforestation, as highlighted in the Article 3.3 provisions of the Kyoto Protocol.

The potentiality of forest and related activities in terms of mitigating climate change can be achieved through following strategies, as stated by Ravindranath et al. (2000): carbon conservation, C_{seq}, and carbon offsetting. According to this, SRF is a part of C offsetting technology; a C offsetting idea was originally proposed by Dyson (1977). Afforestation and reforestation programs can regulate the C cycling of the terrestrial ecosystem, thus providing a potential option to curb climate change. It has been reported that an SRP area of 40 million hectares could reduce the annual C emission by approximately 0.072 Gt (Singh and Lal 2000). It is believed that managed forest plantations have more efficient C storage than natural plantations. Plantations of fast-growing species with intensive management would possibly capture and store more C than other systems (Chauhan et al. 2017b). Therefore, it is necessary to understand the C fluxes inside the plantation forestry, as depicted in Fig. 2. It is noted that C storage in plantation forestry is for the short term as compared with forest ecosystems, due to frequent harvesting.

C_{seq} in SRF indicates the removal and storage of C in tree biomass and soil ecosystems. C_{seq} denotes the amount of C balance that is taken and stored during photosynthesis and lost during respiration (Montagnini and Nair 2004). Originally, the concept of SRP originated with the production of higher biomass to replace fossil fuels (Laureysens et al. 2004a, b). Studies on SRF C_{seq} potential have received

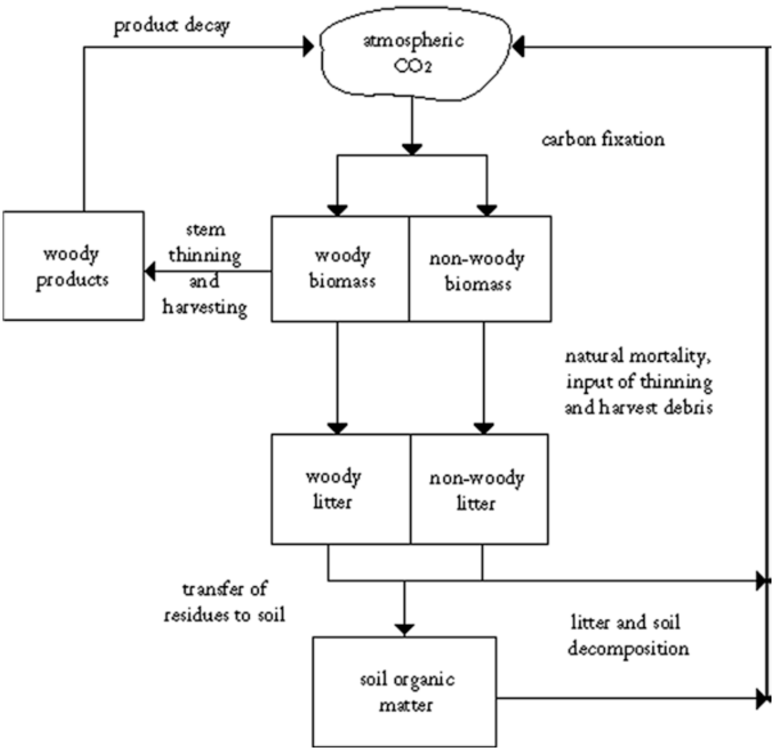

Fig. 2 C cycle in a plantation forest ecosystem. (Cannell 1995)

increasing attention in the last few decades around the world. However, information on C pools and fluxes inside SRF plantations is still meager (Grigal and Berguson 1998; Zha et al. 2004). The emergence of SRF could provide a potential option to mitigate climate change through C_{seq} due to its fast-growing nature (Vitousek 1991). The C storage potentials of some of the fast-growing tropical tree species are presented in Table 7.

Several afforestation and reforestation projects of the CDM can also expedite the introduction of SRP, with a view to optimize the concept of C_{seq}. Under CDM projects, the annexure I countries (developed countries that are bound by emission reductions) are allowed to purchase credits (carbon emission reductions) earned by annexure II countries (generally developing or underdeveloped) so as to meet their target setup per the Kyoto protocol.

The scope of SRF or fast-growing species can be expanded with the introduction of new plantations in degraded areas or wastelands. Agroforestry, a sustainable land use system in which tree components are deliberately cultivated along with agricultural crops, has the potential to sequester C to a considerable extent (Jhariya et al. 2015; Singh and Jhariya 2016; Meena et al. 2015). The dimension of short-rotation or fast-growing species can be explored in an agroforestry system where

Table 7 Examples of tropical forest plantations' carbon storage potential (Schroeder 1992)

Species	Final yield (m^3/ha)	Rotation (years)	Mean annual growth (m^3/ha/year)	Wood density (g/cm^3)	Mean carbon storage (tC/ha)
Pinus caribaea	300	15	20	0.46	59
Leuceana spp. (poor site)	72	8	9	0.60	21
Fuelwood crop	140	7	20	0.60	42
Casuarina spp.					
Moderate site	140	10	14	0.83	55
Degraded site	50	10	5	0.83	21
Pinus patula	400	20	20	0.45	72
Cupressus lusitanica	340	20	17	0.43	57
Acacia mearnsii	250	10	25	0.60	78
Cassia siamea	100	10	10	0.58	28
Acacia nilotica					
Moderate site	60	10	6	0.60	17
Degraded site	45	15	3	0.60	12
Azadirachta indica	40	8	5	0.52	8

fast-growing tree species such as poplar, eucalyptus, subabool, kadam, Malabar neem, white mulberry, and Indian heaven tree, among others, can be incorporated. Basically, the introduction of fast-growing species would aim to maximize biomass production with intensive cultivation techniques, thereby assuming that C storage in the agroforestry system will be increased in the short term. The tradeoffs between C storage and biomass production can be maximized by a conversion of monocropping into agroforestry, which can bring a paradigm shift by increasing the C storage residency. Thus, the effects of SRF would be applied for shorter period of time because the harvesting cycle of a tree species is less than that of a traditional forest; most of the C would return back to the atmosphere, but this problem could be solved by use of durable products made from that wood (Schroeder 1992).

However, the profitable advantages of short-rotation species—ensuring early returns, providing secure income for farmers' income, and capturing C (atmospheric) at faster rate in a shorter period of time—can be crucial while curbing the climate change. The rate of C sequestering is affected by the inherent quality of tree species to store C both in growing and wood products and soil recalcitrant C content (Montagnini and Nair 2004). SRF is established to meet biomass consumption and energy production, while at the same time attention has been shifted to the C_{seq} potentiality in the foreseeable future. However, the establishment of plantations may be dependent on various factors such as climatic, socio-economic, edaphic, and other management interventions related to SRF. Thus, SRF can be view optimistically as an option for long-term C_{seq}.

Gera (2012) reported that fast-growing poplar block plantations in India can sequester 1.33 tC/ha/year without wood products and 2.41 tC/ha/year with wood products. In Uttarakhand, India, Kanime et al. (2013) also assessed the C_{seq} potential of six different tree species plantations, where poplar block plantations

Table 8 C_{seq} potential (above and below ground) of selected SRF around the world

Country	Species	C_{seq} potential (Mg C/ha/year)	References
China	Poplar and willow	3.45	Meifang et al. (2017)
Italy	*Salix alba*	1.3	Calfapietra et al. (2015)
Italy	*Populus alba*	2.0	Calfapietra et al. (2015)
Italy	*Populus×euramericana*	2.0	Calfapietra et al. (2015)
India	*Eucalyptus tereticornis*	6.0	Kaul et al. (2010)
India	*Populus deltoides*	8.0	Kaul et al. (2010)
USA	Hybrid poplar	1.8–3.0	Updegraff et al. (2004)
Canada	Willow (*Salix spp.*)	2.96	Zan et al. (2001)
Sweden	Salix	3.5	Rytter (2012)
Sweden	Poplar	4.0	Rytter (2012)

(2.75 MgC/ha/year) and shisham plantations (2.73 MgC/ha/year) achieved the highest C_{seq} potential. The lowest (0.84 MgC/ha/year) C_{seq} rate was observed in forest red gum boundaries. Fang et al. (2007) reported that 10-year-old poplar plantations in China have the capacity to store 6.23 tons/ha/year of C. Some examples of the SRF C_{seq} potential around the world are presented in Table 8.

Soil C_{seq} potential could add another dimension to the long-term sustainability of SRF. There is huge scope for C_{seq} potential in soil because soil contains the largest C pool in the terrestrial ecosystem, with approximately 1500–1600 pg C in 1 m soil (Post et al. 1982; Amundson 2001). The great potential of C_{seq} is drawing considerable attention for climate change mitigation and adaptation approaches. In general, tree-based land use systems have more SOC than treeless systems. The dynamics of soil organic matter are frequently associated with disturbances in the soil system due to changes in land use or cropping patterns, which ultimately affect soil organic C_{seq} (Jobbagy and Jackson 2000; Guo and Gifford 2002; Degryze et al. 2004).

Afforestation and reforestation programs optimize the value of soil's C_{seq} potential by converting degraded and wasteland areas into bio-energy production plantations. The application of proper management practices, species characteristics, prevailing climatic conditions, edaphic factors, and previous land use pattern will have a significant influence on the C storage potential of a plantation (Post and Kwon 2000). There are reports suggesting that SOC stock shows variations among different plantations of fast-growing species. For example, Keith et al. (2015) assessed the soil C stock changes in different plantations consisting of 9 coniferous and 16 broad-leaved SRF. The authors found that coniferous species had more SOC stock compared with broadleaved SRF, indicating that the effects are species-specific as well as soil type interactions. Species with the potential to produce higher root biomass will have more SOC sequestration in the soil (Lorenz and Lal 2005).

Paul et al. (2002) indicated that there was a positive change in the organic matter content of approximately 0.06 tons/ha/year after the establishment of afforestation activities in former arable lands. Similarly, Post and Kwon (2000) claimed that the afforestation of arable land with different species had a mean positive change in soil

C accumulation of approximately 0.34 tons/ha/year. The soil organic C_{seq} under SRF of willow and poplar was assessed by Rytter (2012) in Sweden; reported that poplar plantations (0.52 MgC/ha/year) had more soil C_{seq} value than did willow plantations (0.41 MgC/ha/year). A study conducted by Deckmyn et al. (2004) revealed that poplar in SRP had more emission reduction potential than mixed oak-beech forest. However, there are reports of no changes or decreases in soil C after afforestation. For example, Dowel et al. (2009) observed that there was decreased soil C content during the first 5 years of plantation, but also stated that losses did not persist as the age of plantation increased. Losses or no change in soil C during the early stages of plantation were also reported by Coleman et al. (2004) and Ulzen-Appiah et al. (2000). In the short term, increases in soil C after afforestation did not show significance improvement for at least 30 years, signifying that more C stocks in soil are present in older plantations (Vesterdal et al. 2002).

In long-rotation plantation, there is longer C storage than in fast-growing SRF, which is self-explanatory and reported in several studies (Sharma et al. 2016; Kaul et al. 2010; Sihag et al. 2015). Compared with natural forests, fast-growing SRP has been established where lands are degraded, on former arable land, or under agroforestry systems. In such cases, fast-growing SRP can account for short-term C storage reservoirs. Because of the fast-growing nature of SRF, there may be high net annual accumulation of C in the biomass, but it tends to reach equilibrium biomass shortly (Kaul et al. 2010). It is evident that growing hybrid poplars for very short rotations (4–6 years) may cause a loss in soil C. The cultivation of such species with a minimum rotation of 12 years could greatly help to sequester soil C (Hansen 1993).

12 Climate Change Mitigation and Adaptation Through SRF

The changing climate and its potential effects on mankind and vegetation of various forms have caused authorities to investigate solutions to tackle these unwanted problems. Mitigation and adaptation activities are being considered to combat the effects of climate change and to meet sustainable development goals. In general, mitigation activities attempt to reduce the unwanted effects of climate change, either by reducing the emission of GHGs or implementing interventions that will increase the sink of GHGs. Adaptation aims to reduce the degree of susceptibility of climate change or adapt to the changing climate by implementing different interventions (IPCC 2002; Locatelli et al. 2015).

Several mitigation and adaptation strategies in the agriculture and forest sectors have been explored in the literature. The forest ecosystem contains a significant amount of total earth C and plays a moderating role in the global climate. Following the emergence of IPCC in 1988, approaches have been made to curb climate change. The forestry sector is considered as a potential area to cope with the unwanted effects of climate change. Strategies and actions have been described in IPCC assessment reports, with a focus on the potential role of forestry and other related sectors to address climate change mitigation and adaptation. Some notable programs (e.g., REDD, REDD++, CDM) were formed as important mitigation and adaptation approaches related to forestry. Plantation forestry has been expanding at a rapid pace during the past few decades. SRF plantations consist of fast-growing tree species, signifying a huge opportunity to increase the C sink in a shorter period of time, as well as to address the scope of mitigation processes. However, due to their fast-growing nature, the plantations are harvested frequently. The limited C storage in wood and other parts is emitted back into the atmosphere through combustion, thus causing a conflict while attempting to address the role of SRF in climate change mitigation.

Theoretically, SRF will help to reduce GHG emissions in two ways, as described by Samson et al. (1999): (a) increasing the C storage capacity of tree biomass and SOC; and (b) replacing fossil fuels or conserving renewable resources by periodically harvesting under SRF. Because of the importance of SRF in increasing the forest cover area, plantation forestry around the work has focused attention on SRF establishment.

12.1 Mitigation and Adaptation Options with SRF

The following are some important mitigation and adaptation options that can be achieved through SRF:

1. Afforestation and reforestation activities: The pace of afforestation and reforestation activities has been stepped up with the introduction of CDM projects from the Kyoto Protocol. Since then, several afforestation and reforestation activity programs have been expanding across different regions of the world. Plantations with fast-growing tree species have also been extensively used for this purpose. Afforestation and reforestation programs are considered to be potential climate change mitigating options and have been implemented in various parts of the CDM projects.
2. Agroforestry: Trees form the integral part of any agroforestry system. The inclusion of fast-growing tree species in agroforestry systems is a viable and promising option. The inclusion of fast-growing tree species appeals to farmers because of the early economic returns and other intermediate products derived from this system. The C_{seq} potential of agroforestry systems has been studied and reported by different researchers around the world. A poplar-based agroforestry system in the Indo-Gangetic plains of India is one of the important systems in this aspect. Moreover, the area of agroforestry is expanding. Different stakeholders are gaining interest in agroforestry and consider it to be an important climate-resilient cropping system.
3. Industrial plantations: Many developed countries have expanded the scope of plantation forestry by introducing industrial plantations with an aim to provide raw materials for pulp wood and other wood-based industries. The fast-growing nature of SRF has advantages over conventional plantation systems because the trees are harvested at regular intervals of time and the demands of industries can be met. C_{seq} forms the basis for mitigation options, and the plantation of native species should be considered as an adaptation approach for changing climates.

4. Bioenergy plantations: The concept of SRF originated to replace fossil fuels by producing higher biomass for fuel wood and energy consumption. C_{seq} and soil C improvements under SRP have attracted the attention of different researchers. However, more information is still needed to validate their results.
5. Wasteland development: The areas of plantation forestry can be extended by covering degraded and wasteland areas. The selection of native fast-growing species has an advantage over exotic species. Agricultural lands that have been intensively farmed can turn into unproductive land, which can then be used for plantation forestry. The establishment of plantation forestry on such lands will require sufficient government funding and other facilities. However, considering the needs for the expansion of forests and tree cover, such activities will play a vital role in fightin climate change.

In general, the mitigation and adaption approaches discussed here have great potential in combating the effects of climate change. However, plantation activities (afforestation and reforestation) can cause some unwanted results, which may hamper environmental values and other social issues. Therefore, there is a need to consider the activities of afforestation and reforestation with an aim to increase the C_{seq} potential, conserve SOC, and meet the requirements for fuel wood and other industrial raw materials (IUCN 2004).

13 SRF and Ecosystem Sustainability

The state of an ecosystem is dynamic, not static. Several factors are responsible for the maintenance of ecosystem sustainability. This implies that the ecosystem's processes tend to change over the course of time—not only from interactions among the components of the ecosystem, but also from human interference or external factors that exert an impact on the sustainability of the ecosystem (Chapin et al. 1996). In the context of ecosystem stability or sustainability, it is generally accepted that natural forests are more complex and superior than plantation systems. Some concerns have been raised over plantation forestry, which is causing harmful effects on environmental processes, such as water issues (quality and quantity), biodiversity status, degradation of soil nutrients, and soil fertility, among others. This controversial situation may be an obstacle to the establishment of SRF and affect the potential of SRF. However, despite these controversial issues, SRF has been considered as a sustainable production approach for more biomass and as a potential platform to sequester CO_2. Thus, it can be seen that SRF versus ecosystem sustainability has become a burgeoning debate topic that provokes different opinions and assumptions, making this issue more ethical than scientific. In this regard, Cossalter and Pye-Smith (2003) compiled and shared the perspectives of fast-growing forestry by analyzing the opinions of different scholars who supported and opposed SRF. According to the authors, several important environmental factors have to be considered when analyzing the impact of SRF on the environment, including biodiversity, soil, and water.

Despite these problems related to environmental issues, SRF practices have been increasing day by day, ensuring the demand for wood and other wood products is met. For example, approximately 90% of the demand for wood-based industrial raw materials in India is mostly supplied through fast-growing tree species plantations (Prasad et al. 2009). SRF programs would able to maintain the ecosystem sustainability by exaggerating the tree covers in wastelands and degraded areas; this process will help in the restoration of degraded and fragile ecosystem. Interestingly, SRF not only attempts to meet the demands for wood for various uses, but it also reduces the pressure put on limited natural forests, literally preventing the act of deforestation. According to the World Forest Movement (1999), SRF has issues related to high demands for water, which could be a major setback in the establishment of SRF, especially where the land is considered for agricultural purposes. However, SRF has been reported to be successfully grown with sewage water applications; thus, the problems of water scarcity in the areas of SRF can be compensated for by such activities (Cossalter and Pye-Smith 2003; Roygard 1999). Moreover, the application of sewage water to SRF will help to solve the problem of water scarcity in SRF areas and minimize the crisis of sewage plant treatment. Phytoremediation is another possible benefit of SRF because fast-growing tree species, such as poplars and willows, can help to improve the soil toxicities of different hazardous compounds (Glass 1999). Phytoremediation through poplars and willows has been extensively studied around the world, as reported by Jackson and Attwood (1996), Hammer et al. (2003), and Laureysens et al. (2004a, b). The establishment of SRF on degraded and fragile land also can enhance the biodiversity of a particular area. Zurba (2016) reported that SRF on degraded land can improve an ecosystem's structural and functional quality by 43% and 12%, respectively.

Thus, it is clear that SRF aims to produce higher biomass for energy consumption and reduce the use of natural resources. Furthermore, it should be considered as a C conversion technology in the field of bioenergy to reduce GHG emissions (Styles and Jones 2007). However, the problems of SRF related to environmental issues also need to be addressed. Proper planning and management of SRF will not only satisfy the need for wood but can also improve the environment (Cossalter and Pye-Smith 2003).

14 Future Implications of SRF

The advantages of SRF for the production of higher biomass in general and as a platform for C storage (biomass and soil) need to be investigated. Limited information has been published in the past few decades; thus, more studies need to be conducted. Europe and other developed countries have shifted from the cultivation of agricultural crops to SRF for several reasons, especially for higher biomass energy. Therefore, C_{seq} needs to be emphasized, along with the broader future implications of SRF use around the world. Some of the important steps that need to be highlighted for the future use of SRF include the following:

- The use of native or indigenous tree species and more research on species adaptability need to be addressed.
- Policy incentives, subsidies, and other financial supports need to be strengthened.
- The required project funds need to be allocated to different stakeholders, such as the private sector, nongovernmental organizations, and farmer groups.
- More afforestation and reforestation activities need to be established in wastelands and unutilized lands.

15 Way Forward to Promote SRF in India

Several programs have been introduced to achieve more progress in plantation forestry in general and SRF in particular, with an aim to meet the goals of sustainable development. To advance these activities, the following strategies should be adopted when SRF is to be established:

(a) Commercially important species of SRF should be prioritized in each agro-ecological zone of India by the government in collaboration with research institutes.
(b) Barren land, wasteland, and village community land should be selected for raising SRF species.
(c) Quality planting material for these SRF species should be provided to farmers/villagers for raising SRF.
(d) Equal benefits should be shared among villagers who are raising SRF. A joint forest management model can be adopted for the management, monitoring, harvesting, and sale of these SRF species.
(e) New policies should be framed to cover these activities, and wood-based industries should be linked with the growers for maximum revenue and sustainable utilization of SRF.

16 Conclusion

SRF initially originated to replace fossil fuels by producing higher biomass for fuel wood and energy consumption purposes. Some common fast-growing tree species, such as earleaf acacia, babool, khair, mangium, siris, jerusalem thorn, neem, Indian heaven tree, beech oak, longbeak eucalyptus, subabool, bakain, khejri, kikar and arjun, poplar, black locust, and willow, are generally used for SRP. SRF plantations serve as a major source of raw material for wood-based industries in India and other countries. Some of the forerunners in terms of SRF plantation area around the world include Brazil, China, Indonesia, Malaysia, the United States, India, the Philippines, and Thailand. Among the SRF plantations, *Eucalyptus* spp. covers the most area, with India accounting for approximately 10% of the world's eucalyptus plantations. SRF aims to meet the demands of wood-based industries, reduce pressure on forests, and provide higher and early returns to farmers in comparison with commercial forestry.

The strengthening of policies and other required incentives need to be emphasized when appraising the role of SRF. Soil sustainability in SRF is mainly dependent upon the previous land use pattern. The impact of SRP on soil properties is either negative or positive. Generally, there is an initial decline in SOC, with a later recovery of the SOC in a due course of time. Similarly, SRF plantations also have a significant impact on the biodiversity of a particular site: Because SRF is generally composed of a single species, SRF may have lower species richness than a natural forest. However, the results may be positive when the SRF is established in areas other than natural forests.

Currently, climate change and its associated phenomena have created an imbalance in ecosystem productivity and sustainability. In response to this challenging situation, tree-based land use systems are being considered as a viable option for mitigating and adapting to climate change. In this context, SRF will help to reduce GHG emissions by increasing the C storage capacity of tree biomass, replacing fossil fuels, and conserving renewable resources by periodically harvesting under SRF. However, studies on C_{seq} potential and SOC have been limited in the past few decades, so more information is still needed to validate the results. The introduction of SRF as part of afforestation and reforestation programs under CDM projects, industrial plantations, bioenergy plantations, and agroforestry systems would add another dimension to climate change mitigation and adaptation approaches. Limitations pertaining to the establishment of SRF include environmental and social issues; however, these problems are more ethical than scientific, and most of the issues related to SRF are region specific. Therefore, the proper execution and management of SRF will be highly essential for the successful establishment of SRF. Prioritizing the importance of native species would encourage the involvement of local people. However, the establishment of plantations may be dependent on climatic, socio-economic, and edaphic factors, as well as other management interventions related to SRP. Thus, the implementation of SRF as an option for long-term C_{seq} remains an optimistic viewpoint.

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Strategies for Combating Climate Change

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Contents

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Abstract

The confusing and increasingly unpredictable climatic conditions and unsustainable human activities have created adverse impacts on the environment. Recent researches by the Columbia University (2018) showed that the earth is in the midst of a 40-year-long global warming drift instigated by human activities. As per NASA report since 1880 climate change records began, the first half of the last 4 years – 2015, 2016, 2017 and 2018 – all take the highest four hottest recorded periods ever documented. Presently, the average surface temperature on earth between January and June, 2018, is the third hottest half-year on record. Major issues such as natural hazards have been triggered by unguarded anthropogenic activities. This has awakened the public to the reality of a threatened environment as the effects of these problems continue to increase. Added to these, there are emissions from gasoline vehicles and industrial activities which give off huge amounts of hydrocarbons which can contribute to health problems. These corresponding global consequences of climate change issues have increased the need for nations to stride towards compulsory climate change responsibility and strategies to minimize these effects. Research and studies need to be designed considering future climatic trends as well as policies for environmental management and sustainability.

Hence, this chapter orchestrates the salient information about components of environmental management and agroforestry as adaptation measures for the minimization of climate change. Environmental management measures elaborated in this study include the enforcement of polices on air quality and land degradation and the minimization of automobiles and industrial waste emissions that hugely contribute to atmospheric pollution of hydrocarbons. Agroforestry measures discussed on include the promotion of afforestation, agriculture, intensive forestry activities, environmental greening and conserving existing forest reserves in both rural and urban areas. These measures are highlighted as having the capability of minimizing climate change by reducing the extent to which greenhouse gases (GHG) deplete the ozone layer that protects the earth. Obviously, the implementation of key policies and making investments will effectively deal with climate change. The phasing out of fossil fuel automobiles, campaigns against deforestation/tree felling, energy efficiency, technology application and capacity building and information dissemination are basically expedient measures for global climate resilience.

Keywords

Agroforestry · Climate change · Environment · Greening · GHG · Hydrocarbons · Pollution

Abbreviations

AFS	Agroforestry systems
C	Carbon
CDM	Clean development mechanism
CFCs	Chlorofluorocarbons
CO_2	Carbon dioxide
CSP	Carbon sequestration potential
GHG	Greenhouse gases
HI	Hedgerow intercropping
PAH	Polynuclear aromatic hydrocarbon
PAN	Peroxyacetyl nitrate
PAs	Protected areas
REDD	Reducing emission from deforestation and forest degradation
SOC	Soil organic carbon
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

Over the years, climate change has gone beyond mere speculations, predictions or a scientific phenomenon to become the weather – monster of our time. Recent global weather-related crisis has brought about land degradation, landscape destruction, poverty and loss of animal, plant and human lives. This has awakened world leaders, researchers and nations to seek possible solutions towards dealing with the situation. United Nations Framework Convention on Climate Change (UNFCCC 2015) inferred that climate change is a change that is distributed directly or indirectly due to human activity, which can alter the composition of the global atmosphere.

Recently, majority of the climate scientist affirmed that variations in the world climate have been caused by anthropogenic activities. These activities include pollutions emanating from industrial activities like mining, burning of fossil fuels, petrochemicals and refineries and deforestation that produce greenhouse gases (GHG). Greenhouse effect increases surface temperatures by about 30 °C by trapping heat emitted from the earth's surface (Pearce 2003; Pierrehumbert 2004; Meena et al. 2016). Considerably, vegetation losses from agricultural and mining activities have contributed to 13 million hectares of forest annually (FAO 2006; Akanwa et al. 2017).

The atmosphere is made up of a several mixtures of gases, water vapour and a variety of fine particles. These atmospheric compositions are responsible for creating conditions that are environmentally sustainable for a healthy biosphere on earth. However, the levels of pollutants discharged into the air are diluted, chemically modified and released on the earth's surface.

On a global scale, the pollutants account for almost 98% of the total pollutants, whereby hydrocarbon contributes about 12% of this amount. The percentages may vary depending upon the locality and the local condition of an area (Amdur 1986). The sources of these gaseous pollutants are both natural and anthropogenic.

All gaseous effluents, vapour and fine particulate material which escape into the atmosphere are eventually released to earth's surface. With regular release of large quantities of particulate materials, fumes, vapour and gases are discharged into the atmosphere causing significant negative influence on plants and animals. They may react, re-react and form harmful and irritating products that can cause ozone depletion as they enter the stratosphere. Other gaseous effluents may settle down, while others may be brought down by precipitation. Most of the injurious materials are held within the atmosphere.

This happens to make a huge impact on air quality indicating the need to enforce air quality standards that are capable of reducing motor vehicle pollution. This includes changes in the technology, policy reformation, intensive agroforestry, urban and rural greening and driving habits that can minimize fuel consumption for consumers and operators. These environment-friendly actions are geared towards climate change responsibility as expedient in order to safeguard the present world's environmental situation from the impacts of climate change. Therefore, this chapter orchestrates the salient information about components of environmental management and agroforestry as adaptation measures for the minimization of climate change.

2 Global Hydrocarbon Emission as a Key Factor in Climate Change Problems

Hydrocarbons are responsible for atmospheric pollution and equally contribute to the greenhouse effect, global warming and global climate change (Arellano et al. 2015; Dewulf and van Langenhove 1999). The continued increase and emission of atmospheric carbon dioxide (CO_2) and other GHGs over the last century have remained as an intractable phenomenon. With faster annual rates of carbon (C) accumulation at 3.5Pg (Pg = 10^{15} g million tons) in 2012, CO_2 rate estimates had increased up to 9.7Pg (Paustain et al. 2000; Peters et al. 2013; Ashoka et al. 2017). This increase is mainly due to burning of fossil fuels, cars, power stations, factories, kerosene used for cooking and lighting in African nations and aggressive forest conversion for agricultural activities (Paustain et al. 2000).

Hydrocarbons are organic compounds primarily made up of hydrogen and C with potentials of becoming the world's major atmospheric pollutant. Most kinds of fuel have hydrocarbons with stored energy. Coal, oil and natural gas all have hydrocarbons in them. Some examples of some hydrocarbons are methane (CH_4), butane (C_4H_{10}), propane (C_3H_8), benzene (C_6H_6), ethane (C_2H_6) and hexane (C_6H_{14}). Most hydrocarbons in existence are naturally sourced from crude oil. Others include biological decomposition of organic materials, natural gas, volatile emission, incomplete combustion of fossil fuels and biomass, automobile exhaust, etc. are some of the sources of hydrocarbons in the atmosphere (Asthana and Asthana 2012). There are different types of hydrocarbon compounds such as methane, aromatic hydrocarbon, alkanes, cycloalkanes and alkyne. Harmful effects caused by hydrocarbons in the atmosphere vary from compound to compound. Hydrocarbons contribute to the release of greenhouse effect which invariably causes global warming and hence climate change. They also deplete the ozone layer, increase the possible occurrence of cancer and respiratory disorders, reduce the photosynthetic ability of plants and ultimately degrade the environment. Hydrocarbons and their classes are discussed in this chapter to further reveal their individual characteristics, sources, uses and potential effects on the environment.

(a) *Methane*

Methane is a gaseous hydrocarbon and also GHGs symbolized as CH_4. Methane gas is produced by two main processes, namely, microorganisms and anaerobically. These processes convert organic compounds into methane. The precise contributions of the six major sources of atmospheric methane are wetlands (22%); enteric fermentation in animals and animal wastes (20%); coal mining, natural gas and petrochemical industry (19%); flooded rice fields (12%); biomass burning (8%); and landfill (6%) (Heilig 1994; Ruddiman 2003; Bubier and Moore 1994). The most important sink in the methane cycle happens to be methane reaction with the hydroxyl radical, which is photochemically produced in the atmosphere. Production of this radical and its large effect on atmospheric concentrations is yet to be fully understood. This uncertainty is exemplified by the observed increase shown between the years 2000 and 2006 as atmospheric concentration of methane ceased for reasons under investigation (Kirschke 2013).

The atmospheric concentrations of methane have increased over time since the inception of the Industrial Revolution exceeding its natural range. Methane gas is 25 times more effective in radioactive reactions than CO_2 at a 100-year time horizon (Forster et al. 2007). Its importance in global climate has been increasingly recognized (Kort et al. 2008; Montzka et al. 2001; Dadhich et al. 2015; Raj et al. 2017, 2018). Global methane concentration has risen from 722 part per billion (ppb) in the pre-industrial era to 1800 ppb in 2011 in recent past (Myhre et al. 2013).

It has an estimated lifetime of 8.9 ± 0.6 years in the atmosphere (Wuebbles and Hayhoe 2002). Methane produced from anaerobic decomposition of organic materials by methanogenic bacteria is released into the atmosphere through three pathways (Tian et al. 2012). Bacteria-generated methane is considered to contribute about 80% (±10%) of the total methane emission, while nonbacterial methane contributes 20% (±10%).

Recent studies suggest that methane reacts with stratospheric chlorine to form hydrochloric acid and thus exerts a protective influence on ozone concentration by eliminating the ozone-depleting chlorine content from the medium (Asthana and Asthana 2012).

(b) *Chlorofluorocarbons (CFCs)*

CFCs are another group of hydrocarbon that is of great concern in the atmosphere. They are non-toxic, colourless, odourless inert chemicals that persist in the atmosphere for very long time. CFCs find widespread use in refrigeration, air-conditioner, foam blowing and spray can and as solvents. Concern about ozone layer depletion by CFCs grew in 1974–1975 in papers, which identified photochemical reactions linking the buildup of CFCs in the atmosphere to ozone destruction in the stratosphere. CFCs linger for about 50 to 100 years atmospherically before they are broken down. An alternative to both CFCs and burning of fossil fuel exists, but global adoption requires planning and financial investment by countries (Godlee and Walker 1991). Most developed countries have endeavoured to reduce CFCs emission, but Third World countries are still struggling with the transformation to more environment-friendly methods.

(c) *Aldehydes*

Aldehyde compounds play an important role in the atmospheric chemistry as potent chemical pollutants which can have potentials for adverse health effects on humans and the environment (Lipari et al. 1984; Villanueva et al. 2015). Chemicals in this family can be divided into subclasses based on corresponding structures that incorporate additional functional molecules: (1) short-chain, unhindered aldehydes, formaldehydes and acetaldehyde; (2) long-chain alkanals and nonanal; (3) aromatic aldehydes, benzaldehyde and vanillin; (4) α,β-unsaturated aldehydes that include numerous subclasses, aromatic alkenals, short- and long-chain alkenals and hydroxy or oxoalkenals; and (5) α-oxoaldehydes, glyoxal and glycolaldehyde (Feron et al. 1991; O'Brien et al. 2005). Aldehydes are formed in the atmosphere as a result of photochemical oxidation of reactive hydrocarbons and emitted through incomplete combustion of biomass and fossil fuels and (Schauer et al. 2001; Possanzini et al. 2002; Verma et al. 2015). Aldehydes are of critical importance since they are the most stable intermediate species in the oxidation of volatile organic compounds (Granby et al. 1997). There are various combustion sources that generate high molar percentages of reactive aldehydes; these include vehicles, power plants, residential wood burning and forest fires.

There is also generation of volatile aldehydes during cooking and mostly during the use of overheated cooking oils (Conklin and Bhatnagar 2010). In urban areas vehicle exhausts are the primary emission source of these pollutants. Formaldehyde usually accounts for about 50%, while acrolein accounts for about 5% of the estimated aldehydes in polluted air. Formaldehydes in indoor atmosphere are from incomplete combustion of wood fuels, plywood, foam insulators and other objects in which formaldehyde-containing adhesives are used. They are highly reactive chemicals that are rapidly degraded in the atmosphere.

(d) *Aromatic Hydrocarbons*

Aromatic compounds are named because many of its compounds have a sweet or pleasant odour. The configuration of six C atoms in aromatic compounds is known as a benzene ring. Aromatic hydrocarbons can be either monocyclic or polycyclic. Aromatic hydrocarbons are considered to be more toxic than simple aliphatic compounds. Most of the aromatic hydrocarbons present in the atmosphere are derived from combustion of fossil fuel such as coal, tar and biomass (Dewulf and van Langenhove 1999).

Benzene (C_6H_6) is the simplest aromatic hydrocarbon used in industries as solvent and in fuel oils because of its antiknock properties. Benzene may constitute almost 2.0–2.5% by volume of the total amount of hydrocarbon emitted with exhausts of internal combustion engines.

(e) *Polynuclear Aromatic Hydrocarbons*

The term polynuclear aromatic hydrocarbons (PAHs) are organic compounds that may be colourless, white or pale yellow solids containing mostly C and hydrogen atoms. PAHs are chemically composed of two or more benzene rings bonded in linear cluster or angular arrangements. They are a ubiquitous group of several hundred chemically related compounds, environmentally persistent with various structures with varied toxicity (Abdel-Shafy and Mansour 2016).

The major sources of polynuclear aromatic hydrocarbons are incomplete combustion of organic materials such as coal, oil, wood, etc. They are formed in the processes of biological changes and as a product of partial combustion from either natural combustion sources (forest and bush fires, volcanoes, etc.) or man-made combustion sources (automobile emission, cigarette smoke, cooking, incomplete combustion of fuel oil in lighting and heating system, etc.) (Koskela 2000). PAHs are present as volatile, semi-volatile and particulate pollutants as organic substances are exposed to high temperatures under low oxygen or non-oxygen conditions. They are detectable in air, soil and water. The atmosphere is the most important means of PAHs dispersal. It receives the bulk of the PAHs environment load resulting in PAHs being ubiquitous in the environment.

(f) *Peroxyacetyl Nitrate*

Reactions involving hydrocarbons particularly aldehydes and oxides of nitrogen in the atmosphere at times result in the formation of compounds like peroxyacetyl nitrate (PAN) and peroxybenzonyl nitrate. PAN were first identified in the 1950s and are associated with photochemical smog of cities, which are secondary pollutants formed in the atmosphere after the emission of primary pollutants. They are produced in the atmosphere when oxidized with volatile organic compounds in combination with nitrogen oxide.

They play important roles in the chemistry of the troposphere by controlling the rate of ozone production since they are core components of the tropospheric photochemical system. PAN has a relative long life that affects the abundance of nitrous oxide on a global scale since it can be transported over long distance before its thermal decomposition (Crutzen 1979). This means that they can spread their environmental impact to other regions by contributing to air pollution in places beyond their source. The lifetime of PAN in warmer areas is typically a few hours, although at colder temperatures (-20 °C), it lasts for about 3 months. When PAN decomposes, it produces a variety of chemicals like C monoxide and is harmful to the environment.

3 Other Major Sources of Atmospheric Pollution and Climate Change

3.1 Automobile Emissions as a Means of Atmospheric Pollution

When hydrocarbons are burnt along with fuels, CO_2 gas and C monoxide are produced in the process and released into the air (Bonsang and Boissard 1999). Some hydrocarbon, such as volatile organic compounds which make up some of the chemicals found in smog, is emitted from gasoline and diesel vehicles (Ciccioli et al. 1999).

Sources of atmospheric pollutants include smog, acid rain, C monoxide, fossil fuel exhausts and tropospheric ozone (Derwent 1999). The influx of large volume of hybrid vehicles in the USA has not replaced the widespread use of gasoline and diesel vehicles in some developed and developing countries. Across the world, in most major cities, gasoline vehicles are responsible for about 60% of air pollution (Friedrich and Obermeier 1999). These harmful emissions result from partial combustion of fuels causing hydrocarbons to react with nitrogen oxides (produced under high temperatures and excess oxygen). The resultant gases under sunlight exposure form ground-level ozone or smog (Derwent 1999).

Smog is usually associated with low visibility due to the scattering of solar insolation by high concentrations of anthropogenic aerosols (Meszaros 1999). The health hazards of smog are caused in part by the aerosol particles and by invisible toxic gases including ozone, CO, SO_2 and carcinogens present in the polluted air (Buckeridge et al. 2002).

The presence of high concentrations of ozone in smog was first discovered in Los Angeles in the 1950s. Laboratory chamber experiments conducted at the time showed that ozone was generated by photochemical reactions in the atmosphere involving hydrocarbons and nitrogen oxides emitted from automobiles (Meszaros 1999). This atmospheric mechanism for ozone production helped to explain why ozone concentrations are often higher in urban areas. The details of the chemical mechanism were poorly understood until the 1970s (Liang et al. 2017).

Most developing and industrialized countries are fast growing and densely populated coupled with the emission of hydrocarbons. This leads to rapid ozone production and pollution since the volume of hydrocarbon-based driven cars has increased; its engine inefficiency (most gasoline cars in developing countries are old and fairly used) determines the amount of ozone produced. Ozone has high potentials for eye or throat irritations, premature deaths, occurrences of cancer and respiratory disorders and reduces the photosynthetic ability of plants, thereby causing enormous damage to ecosystems (Enhalt 1999). Air pollution is killing young children in sub-Saharan Africa, causing stunt brain development, asthma, strokes and cancers even in growing adults (Laganiere et al. 2010).

3.2 Industrial/Gas Flaring and Release of GHG

The Industrial Revolution combined with more recent industrial activities has triggered emissions of CO_2 and other GHGs that have led to global warming (Paustain et al. 2000). Geological evidence suggested that presently, the world has entered into a period of unusual warming; for the past 400,000 years, C levels in the atmosphere had never exceeded 300 ppm, but from 1950 this level started exceeding and is still on the increase (Friedrich and Obermeier 1999).

In 1990, the mean global temperature increased by 0.3–0.6 °C over the past century; however, for the first time in recorded history, CO_2 levels surpassed 400 ppm in 2003 (IPCC 1990). Increased burning of fossil fuels, cars, factories and industries among others has escalated the emission of GHGs. The global greenhouse percentages for recent decade include electricity and heat production (25%), industries (21%) and agriculture land use (24%) (Meszaros 1999; IPCC 1990; Raj et al. 2018). Also, there are high concentrations of ozone in surface air emitting nitrogen and various reactive hydrocarbons. Nitrogen emission is mainly from fossil fuel combustion (Bonsang and Boissard 1999; Fall 1999).

Heavy industrial activities can result in oil spills causing damage to ecosystems and human health. Oil is not only detrimental in large spills; even small emissions from automotive leaks and other sources can have cumulative negative effects (Brulle and Pellow 2006; Chakraborty 2009).

Generally, it can be deduced that human activities over the years have released excessive hydrocarbons into the atmosphere. These emissions have accumulated to give the greenhouse effect and subsequently brought huge changes in the world's climate (see Figs. 1 and 2, showing the emission of toxic gases and the consequences of human actions such as forest losses in Africa). Hence, undeniable sporadic environmental consequences have become prevalent such as heat waves, rising sea levels, acidification, damaged coral reefs and marine life, flooding and tropical storms, species extinction and many more across the globe (UNEP 2007). Obviously, greenhouse effect, global warming and climate change are environmental crisis triggered by the emission of hydrocarbons into the atmosphere sourced from numerous unregulated human activities. This chapter further discussed two major strategies that can minimize the negative effects of climate change, namely, environmental management and agroforestry systems (AFS).

Fig. 1 Explosion of fuel tanker and gaseous emission from industrial processes

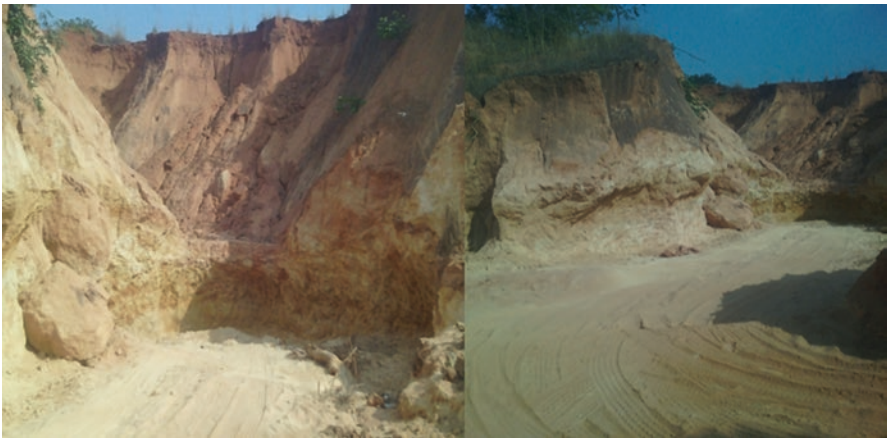

Fig. 2 Forest loss and land degradation caused by human activities. (Akanwa et al. 2017)

4 Environmental Management Measures for Minimizing Climate Change Effects

Environmental management procedures are sustainable in minimizing the emission of atmospheric C and climate change effects without putting pressure on food production and security. In the USA and other industrialized countries, air quality standards (concentrations not to be exceeded) have been used to protect the population against exposure to different air pollutants (Paustain et al. 2000; Dhakal et al. 2016).

When the standards are exceeded, emission controls must be enforced. National legislation for air pollution control in the USA started with the Clean Air Act of 1970. Since then, ozone has been proven to be the most difficult pollutant to bring into compliance with air quality standards (UNEP 2009). In Europe, the USA, Australia and Southeast Asia, there are strong regulations protecting the land surface against the negative impact of human activities.

However, developing countries are facing numerous challenges in terms of policy adaptation and enforcement being surrounded by myriads of problems such as inadequate environmental awareness, corruption and bribery, ethnic crisis, religious clashes, unstable government, poor leadership, poverty and hunger, insecurity and mismanagement of funds and priority, among others. These issues have continued to sabotage policy enforcement in Africa and other developing nations despite the availability of comprehensive policy and legal framework. Hence, tree felling, deforestation, unguarded natural resources exploration and other activities that degrade land surface have continued to persist. Generally, this reflects weakness in policy implementation and enforcement of environmental laws (Olarinde and Orecho 2015).

There is urgent need to strengthen the existing legislation measures aimed at minimizing the exposure of the land surface to environmental degradation through campaigns against deforestation/tree felling, energy efficiency, technology application and capacity building and information dissemination.

Consequently, legislative measures should be introduced to address the weaknesses of the existing regulations specifically and take into account new and emerging environmental threats on the land surface. Furthermore, new developments in knowledge and best practices, as well as the outcomes of new international conventions, should be integrated into the existing environmental laws and policies by all countries in order to make them more responsive to the challenges of climate change.

Furthermore, it is necessary to minimize automobile emissions through developing responsibilities among individuals and companies by government initiatives in order to ensure that vehicle(s) fully burn hydrocarbons and grant health benefits especially to infants. This would enable the vehicles to reduce the volume of harmful emissions produced and improve air quality. Practices like regular car services to maintain the vehicles engine state since built-up and unburned fuel can clog engines and hinder its combustion. Also, by employing a proven fuel additive to unbundle the hydrocarbon molecules, in order, to allow oxygen access and burn completely. Finally, there is need for a gradual replacement of the existing gasoline vehicles with electric or hybrid vehicles which requires a bit of time.

5 Agroforestry as a Sustainable Measure for Minimizing Climate Change

Agroforestry is a measure with the potential to sequester C and mitigate the greenhouse effect and climate change (see Fig. 3 showing agroforestry practice in residential area). Agroforestry reduces atmospheric C and is a sustainable means of effective land management which combines both agricultural and forestry practices (Jhariya et al. 2015, 2018a; Singh and Jhariya 2016). Macdicken and Vergara (1990) and Nair (1993) defined agroforestry practice as a deliberate integration of trees with agricultural crops and livestock either simultaneously or sequentially on the same unit of land.

Similarly, the International Centre for Research in Agroforestry and the World Agroforestry Centre defined the term agroforestry as a dynamic, ecologically based natural resources management system that integrates trees in farmland and rangeland and diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels.

Association for Temperate Agroforestry (1997) in the USA also defined AFS as an integrated land management system that optimizes the benefits from the biological interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock.

Generally, it is a land-use system in which woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land unit as agricultural crops (woody or not), animals or both, either in some form of spatial arrangement or temporal sequence.

In AFS there are both ecological and economic interactions between the different components. Hence, AFS should involve two main components, the trees/shrubs and an agricultural crop (which could also be pasture). All types of AFS integrate people as part of the system as they are artificial systems to a higher (i.e. domestic animals)

Fig. 3 Agroforestry practices in residential dwellings in Nigeria

or lower degree (i.e. wild animals in natural or national parks), where one component can be promoted over the other, or both at the same time, trying to reach equilibrium between the different components (Mosquera-Losada et al. 2009). Studies and detailed literature on agroforestry and its practice have been made by several authors (Nair 1993, 2011; Lal 2010; Medugu et al. 2010 Lorenz and Lal 2014; Roshetko et al. 2002; Gama-Rodngues et al. 2011; Guo and Gifford 2002; Jackson et al. 2002; Katzenstein et al. 2003; Meena and Yadav 2014).

6 Agroforestry Promotion and Their Role in C Sequestration

Promoting biological systems like forests are essential because of their inherent ability to store, capture and release C, thereby enabling plants draw C from the atmosphere. Forests due to their long life and considerable mass are able to store large volumes of C in their cells (Jhariya 2014, 2017; Jhariya and Yadav 2018). Biological decline or destruction such as decomposition or fire destroys the biological material and releases C generally back into the atmosphere (Kittur et al. 2014a, b; Jhariya 2017). Soils are also vehicles to sequester and store C making them rich in C and exceptionally suited for agriculture (Sedjo and Sohngen 2012).

Researchers have revealed that forests and forestry have great potentials in mitigating climate change problems. Effective forest management systems can help in the reduction of atmospheric C in three basic ways. The first is the *C sequestration process* which employs practices such as afforestation, reforestation and restoration of degraded lands, improved silvicultural techniques to increase growth rates and implementation of agroforestry practices on agricultural lands (Jhariya et al. 2018b).

Secondly, *C conservation* approach is applied through the conservation of biomass and soil C in existing forests, improved harvesting practices such as reduced impact logging, improved efficiency of wood processing, protection of forest from fires and more effective use of burning in both forest and agricultural systems. Thirdly, *C substitution* requires the increased conversion of forest biomass into durable wood products for use in place of energy-intensive materials, increased use of biofuels such as introduction of bioenergy plantations and enhanced utilization of harvesting waste as feedstock such as sawdust for biofuel (Bass et al. 2000). However, C conservation has been scientifically indicated to possess the best potentials for rapid mitigation of climate change although not without difficulties.

C sequestration is a long-term process that is applied in the management of atmospheric C. Forestry and agroforestry have been recognized with unique capabilities as a C sequestration strategy because of its applicability in agricultural lands as well as in reforestation and afforestation programmes (Cairns and Meganck 1999; Ruark et al. 2003).

Research interest in soil organic carbon (SOC) as a potential sink for atmospheric CO_2 also increased within the same period (IPCC 2000). The idea was to find a low-cost method to sequester C in the context of increasing concerns about global climatic change. AFS was found to have the potential of reducing atmospheric C because of its net sequestration effect by their ability to capture atmospheric CO_2 and store C in plants and soil (Nair 2011). Agroforestry combines trees and/or shrubs with agronomic crops and also offers great promise to sequester C both above- and belowground. As such agroforestry practices were approved as a strategy for C sequestration under afforestation and reforestation programme and also under Clean Development Mechanism (CDM) of the Kyoto Protocol (Watson et al. 2000).

Studies carried out by many researchers showed that AFS outperformed most other systems (treeless or only trees) in terms of C sequestration both above- and belowground (Lee and Jose 2003; Nair et al. 2009; Matos et al. 2011). The C stored in trees could stay in soils or as wood product for extended period of time. C can be stored for centuries in this form.

Literatures on C sequestration abound; but unfortunately, there are considerable variations existing on the concept of C sequestration that does not signify uniformity. Therefore, there is a little consensus in literature about what the term C sequestration totally means (Nair 2011; Krna and Rapson 2013; Yadav et al. 2017). UNFCC defined C sequestration as the process of removing C from the atmosphere and depositing it in a reservoir. C sequestration is the accumulation of C in territorial as opposed to atmospheric form. It is the process of capture and long-term storage of atmospheric CO_2. Essentially, C sequestered is the difference between C 'gained' by photosynthesis and C 'lost' or 'released' by respiration of all components of the ecosystem, and this overall gain or loss of C is usually represented by net ecosystem productivity.

Most C enters the ecosystem through photosynthesis in the leaves, and C accumulation is most obvious when it takes place aboveground biomass. Majority of the C assimilated is transported belowground via root growth and turnover, root exudates (of organic substances) and litter deposition (UNFCC 2007). Therefore soils contain the major stock of C in the ecosystem (Montagnini and Nair 2004). Sequestration is possible through a range of process including those occurring naturally in plants and soil.

C sequestration occurs in phases: firstly, the quick accumulation phase when the trees are planted; secondly, the maturation period when tons of C are stored in the boles, stems, roots of trees and soil; and, finally, at the end when the trees are harvested and the land returned to cropping as part of the C is released back to the atmosphere (Dixon 1995). Sequestration does not have to end at wood harvest; C storage can continue if boles, stems or branches are processed in any form of long-lasting product.

There is also a lack of consensus over the period of time in which C has to be immobilized in soil before it is considered to be sequestered as a useful contribution to climate change mitigation (Krna and Rapson 2013; Mackey et al. 2013). This process of biologically mediated uptake and conversion of CO_2 into inert, long-lived C-containing material is called bio-sequestration (US DOE 2008). Effective sequestration occurs only when there is a positive net C balance from an initial stock after a few decades (Feller et al. 2001). Fig. 4 showed the forest C sequestration cycle which is the movement of C from the atmosphere to forest and soil, back to the atmosphere.

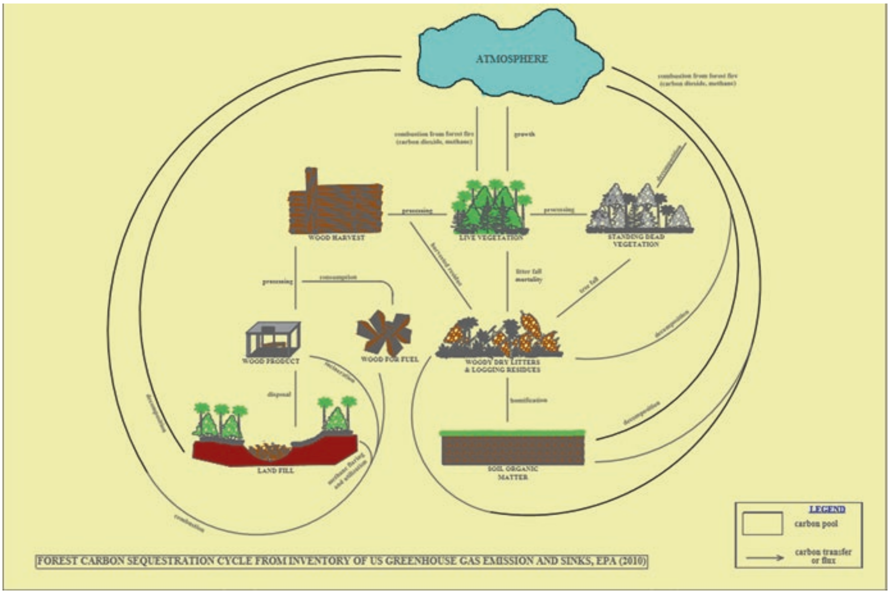

Fig. 4 Schematic diagram showing forest C sequestration cycle. (Source: EPA 2010)

In AFS, C is located in five main pools, namely, aboveground plant biomass (tree and understory), plant roots (tree and understory), litter, microbial and soil C. These pools interact with each other via different pathways of changes and movement. There are a number of factors that determine the amount of C in each pool. These factors include ecoregion, type of system, site quality and previous land use (Nair 2011). Other factors can also include tree species and system management (Albrecht and Kandji 2003).

7 AFS Practised in Different Regions and Their C Storage

AFS are environment-friendly tools that are sustainable in minimizing the emission of atmospheric C and climate change (Akanwa et al. 2019). AFS can be grouped into agrisilvicultural system which includes improved fallow, taungya, alley cropping/hedge intercropping, multipurpose trees on crop land, plantation combination, home garden, trees for soil conservation and reclamation, windbreaks and shelterbelts, living fences or hedges between fields, fuel wood products, multilayer tree gardens and forests farming.

Second is the silvopastoral system which uses trees on rangeland or pastures, fodder/protein banks, plantation crops, pastures and farm animals. Thirdly, the agrosilvopastoral systems are made up of home gardens with animal production, multipurpose woods hedgerows and riparian buffer, and fourthly, apiculture practices involve trees on farmlands, aqua-agroforestry and multipurpose wood lot. (For details on the different AFS and practice, the reader is referred to Macdicken and

Table 1 C storage potential of AFS in different ecoregions of the world (Albrecht and Kandji 2003; Murthy et al. 2013)

Continent	Ecoregion	System	Potential ($MgCha^{-1}$)
Africa	Humid tropical high	Agrosilviculture	29–53
South America	Humid tropical low dry lowlands		39–102 39–195
Southeast Asia	Humid tropical dry lowland		12–228 68–81
Australia	Humid tropical lowland	Silvopastoral	28–51
North America	Humid tropical high, humid tropical low, dry lowlands		133–154 104–198 90–175
North Asia	Humid tropical low		15–18

Vergara (1990); Nair (1993); Leakey (1996); and Muschler (2016)). Agroforestry practices in the different ecoregions of the world, though very similar, have some variations due to the prevailing conditions and species of plants and animals found in each region. Table 1 shows AFS in different regions of the world with carbon sequestration potential (CSP).

AFS can store C in free biomass and soil depending on the environmental and socio-economic factors available. The free components of agroforestry are significant sinks of atmospheric C due to fast growth and high productivity.

The estimates of aboveground CSP for AFS vary considerably. The CSP values are a direct result of the ecological production potentials of the system that depends on the site characteristics, land-use types, species involved, stand age and management practices. Unfortunately, in most cases, the baseline information is either non-existent or is only anecdotal; besides, the methodologies used to derive such estimates often lack the required rigour (Kumar and Nair 2011).

AFS play an important role in the world's C cycle which contains 12% of the world's terrestrial C (Dixon 1995). In AFS systems, its application vary from region to region which can provide different results on C sequestration. The amount of C sequestered by each practice depends on the factors mentioned earlier. Udawatta and Jose (2011) provided a review of C sequestration opportunities available under various agroforestry practices in temperate North America. Some agroforestry practices and their C sequestration are discussed below. This is by far in exhaustive of the different types practised all over the globe.

(a) *Improved Fallow*

Improved fallow is applied by planting few species of crop as a substitute to natural fallow to achieve the benefits of the latter in a shorter time. Using AFS in fallow can ameliorate soil fertility and increase C pool. The magnitude of the improvement depends on several factors including fallow species, length of fallow, density of tree planting, tree management and the soil and chemical conditions (Mutuo 2003).

Improved fallow contributes to soil C sequestration by stabilizing in water-stable aggregates. Significant increase of soil organic matter in the top soil of improved fallow system has been obtained with some crops (Prinz 1986). Rao et al. (1998) distinguished two categories of improved fallow: (1) short-duration fallow with fast-growing leguminous trees or shrubs seeking to replenish soil fertility and (2) medium- to long-duration fallows with diverse species aimed at rehabilitating degraded and abandoned lands as well as exploring tree products for food, fruits and firewood.

Biomass production in planted fallows depends on several factors including the environmental condition, the soil type, the magnitude of land degraded and the length of fallow period. A 6-year study of C sequestration in fallow by Lasco and Suson (1999) in the Philippines showed aboveground *Leucaena leucocephala* (subabool) biomass increased in the first year from 4 $Mgha^{-1}$ to 64 $Mgha^{-1}$ in the sixth year. C stored in the soil and woody debris was estimated at 25% of the aboveground C, while the average C storage was 16 $Mgha^{-1}$ over the 6-year period.

Improved fallow has been widely practised and recommended for its essential roles in better land management and soil improvement. In Western Kenya, improved fallow was found to improve the productivity of degraded soils although the duration of fallow was greatly shortened by land scarcity (Albrecht and Kandji 2003). Some of the studies in Kenya showed aboveground biomass varied between 7 and 43.4 $MgCha^{-1}$ resulting in C storage of 4–22 $MgCha^{-1}$. Belowground biomass was also high especially in 18- and 22-month fallow. The 18-month fallow of *Tephrosia candida* (white hoary pea) produced the most significant root biomass (33.2 $MgCha^{-1}$). Planting fallow trees for 12–22 months in Western Kenya resulted in C input ranging from 1.35 to 16.5 $Mgha^{-1}$ in the soil. Similar studies in Togo showed increased soil organic matter and SOC accretion were estimated between 0.73 and 12.45 $Mgha^{-1}$ (Albrecht and Kandji 2003).

(b) *Hedgerow Intercropping*

Hedgerow intercropping (HI) refers to AFS system where crops are grown between rows of regular woody species. In the tropics, no distinction is usually made between HI and alley cropping (Albrecht and Kandji 2003). HI was initially developed to restore fertility of degraded soils in the humid and subhumid tropics. HI has been adopted in other regions to also help in restoring degraded lands.

Analysis of biomass production in HI system from literature showed strong variations in its C sequestration 91–37 $Mgha^{-1}$. This variation depends on certain factors such as on soil type, climate and system management (Kang 1993; Kang et al. 1999). C storage in HI system may be temporary because the biomass is continuously harvested for pruning (fodder) and firewood. In many areas of the tropics, regular addition of pruning and root turnover over the years have contributed to the buildup of soil organic matter and nutrient stock in the soil (Rao et al. 1998; Kumar et al. 2001).

In Nigeria, Kang et al. (1999) found that in *Alfisol*, *Gliricidia sepium* (Mexican lilac) and subabool increased surface SOC by 15% (2.38 $MgCha^{-1}$). In a 5-year study with *Inga edulis* (ice cream bean) in HI, an increase of 12% in SOC (0.23 $MgCha^{-1}$) was observed (Alegre and Rao 1996). Similarly, when SOC in the 0–15 m layer of HI was compared with a continuous cropping system after 5 years, the measurements were 1.23% in HI, 0.94% in alley and 0.59% in continuous cropping. The study found that 6–10 $MgCha^{-1}$ were stored through HI (Albrecht and Kandji 2003)

(c) *Silvopastoral*

Silvopastoral system is an AFS practice that integrates trees and forage, crops and livestock into a structural and functional system. It is a common system in North and South America. Silvopastoral system can enhance rooting depth and distribution and quantity and quality of organic matter input, thereby improving C sequestration (Haile et al. 2010; Cabbage et al. 2013; Ram and Meena 2014). The greater potential to sequester C by silvopasture was illustrated by Sharrow and Ismail (2004).

In silvopastoral system, the roots of perennial vegetation shifts C deeper into the soil profile, compared to conventional pasture or row crops (Udawatta and Jose 2011). The spatial distribution of C above- and belowground may vary depending on the design of the system and management practices. The tree roots contribute to SOC pool not only in the upper soil but also in the deeper soil profile. In silvopastoral practice, C is deposited on soil via manure deposits from the animals.

When compared, silvopastoral system usually outperforms either forest or pasture in C sequestration as they have both forest and grassland mechanism of C capture that can maximize C sequestration both above- and belowground. In comparison of Douglas fir (*Pseudotsuga menziesii* (Mirb) (Franco)), cool season grass, silvopastoral system with pasture and Douglas fir plantation in Oregon, the silvopastoral system sequestered additional 0.74 $MgCha^{-1}$ and 0.52 $MgCha^{-1}$ year than the plantation and pasture, respectively. Individual trees in silvopastoral system had faster growth and thus ability to store more C.

The above- and belowground C stored in biomass and soil was 5.8 and 8.2 $MgCha^{-1}$ greater in silvopasture than in the pasture and Douglas fir plantation. Trees store about 50–60% of the C in the aboveground biomass, while pasture grass stores only 10% aboveground; the rest are allocated to belowground (Sharrow and Ismail 2004). C is shifted deeper into the soil profile by roots of perennial vegetation in silvopastoral than in conventional pasture or row crops (Udawatta and Jose 2011).

There is a significantly greater root mass in the 1 m soil profile in tree-grass areas than the pasture grass, clearly indicating the potential to deposit C deeper in the soil profile in silvopastoral compared to pasture. In their study, Haile et al. (2010), silvopastoral system had 556 and 105 $Mgha^{-1}$ of SOC in comparison to open pasture which has 94 and 26 $Mgha^{-1}$ SOC up to a depth of 75–125 cm, thus indicating the contribution of tree roots to SOC pool not only in the upper soil but also in the deeper soil.

To further demonstrate the importance of AFS in C reduction in the atmosphere, Lee and Dodson (1996) estimated in South Central USA that the conversion of 3.6

million ha marginal pasture of land to silvopastoral practice with pines could sequester 5.6 TgC year^{-1} for the first 25 years and 1.1 TgC year^{-1} for subsequent 25 years, while if the land is left for pasture, only 0.3 TgC year^{-1} will be sequestered. Similarly Nair and Nair (2003), and Montagnini and Nair (2004) estimated that 70 million ha of silvopastoral system in the USA could store 9 TgC year^{-1}.

(d) *Boundary Planting, Windbreak and Live Fence*

Windbreak and live fence are common examples of boundary planting. The major aim of this system is to protect the area from wind damage. This method can be designed to provide multiple functions and/or products including fruits, animal fodder, wildlife habitat and other economic farm product (Wilkinson and Elevitch 2000).

Live fences comprise two basic categories: (1) living fence posts, these are widely spaced single lines of woody plants supporting barbed wire, bamboo or other materials, and (2) living barriers or hedges, which are thicker and more densely spaced fences that generally include a number of different species and usually do not support barbed wire.

The contribution of windbreak/live fence in the buildup of soil C may not be significant at a field level because of the relatively small proportion of land covered by the trees (Albrecht and Kandji 2003). For example, live fence of Mexican lilac monitored on a 4-year cycle produced a total biomass of 7 Mgkm^{-1} per year (35 MgCha^{-1} per year) when pruned every 4 months and 9.5 Mgkm^{-1} per year (50 MgCha^{-1}per year) when pruned every 6 months. Similar Figs. (30 and 55 MgCha^{-1} per year), respectively, were calculated for *Erythrina berteroana* (coral bean) in the same study (Romero et al. 1991). Baggio and Heuveldop (1984) studied the potential of *Calliandra calothyrsus* (spiked powder puff) as a live fence species in Costa Rica. At 10 months, the total biomass produced was 3–4 Mg dry matter per km of fence (2 Mg C sequestered per km) representing about 20 MgCha^{-1} on average width of 1 m for the fences.

The effect of boundary planting is limited to 10 m on both sides of the tree line (Rao et al. 1998). This suggests that a 50% increase in the C stock around a 100 m tree line would translate into 10% C increase per hectare. However boundary planting can contribute to improvement of the soil condition and indirectly enhance C sequestration by improving crop production and reducing erosion-induced soil losses (Albrecht and Kandji 2003). Biomass production in boundary planting can be highly variable depending upon environment and soil characteristics, tree spacing, pruning frequency and management (Albrecht and Kandji 2003).

(e) *Home Gardens, Multistrata System and Tree Gardens*

Home garden, multistrata tree garden and analogue forest are variants of the complex system of agroforestry. These systems are among the sustainable cropping system in the tropics and are widely practised in Latin America, Southeast Asia and Equatorial Africa, and they involve plant diversity (Fernandes and Nair 1986;

Salafsky 1994; Baijukya and Piters 1998; Szott et al. 1991; Herzog 1994). In the humid tropics, perennial crops such as coffee (*Coffea* spp.) or cacao (*Theobroma cacao*) are commonly mixed with trees like coral bean, ice cream bean and *Corcha* spp. to diversify farm products and to exploit the benefits of tree-crop interactions. The trees help in reducing evapotranspiration with their shades, nutrient cycling and erosion control (Beer 1987; Young 1997). Pruning of the shade trees are done regularly depending on their species to help soil improvement.

In these systems, variation can be high, and productivity depends on several factors which include age, structure and management. A study by Beer et al. (1990) on the breakdown of biomass production over a 10-year period using a two-tree combination in Costa Rica gave 6 $MgCha^{-1}$ per year in shade trees. Soil organic matter in the 0–45 cm layer increased over the 10-year period by 42 and 16 $Mgha^{-1}$ in the cacao branches – *Erythrina poeppigiana* (poro tree) and in the *Cordia alliodora* (Spanish elm) systems which amount to 21 and 8 $MgCha^{-1}$ sequestrated, respectively. The C sequestration capacity of agroforestry calculated by Houghton et al. (1991) for America and Asia were also within similar range. Jensen (1993) studied in Jarash showed that 16 $MgCha^{-1}$ could be stored if rice fields were transformed into home gardens.

In these systems, decline in soil fertility is usually minimal despite continuous harvesting of crops, wood and other products. The soil physical and chemical properties are improved by abundant litter and/or pruned biomass returned to the soil combined with the decayed and decaying roots.

(f) *Taungya Farming*

Taungya farming involves the planting of forest trees in combination with food crops. It has its origins in Southeast Asia (Burma, now Myanmar and Thailand) where it was introduced in a bid to restore tree cover following shifting cultivation. Under taungya, farmers were allowed to cultivate crops among teak (*Tectona grandis*) for the first few years as the seedlings established on degraded forest land. The word ‘taungya’ is Burmese, literally means ‘cultivation on the hills’. It is used to control weeds, reduce establishment costs, generate early income and stimulate the development of woody perennials species. SOC can be higher in taungya and improved fallow than in pasture without trees.

Generally, the most important role that agroforestry and plantations may play is to offset destruction of primary forest by providing the necessary wood products from land that has already been cleared (Montagnini and Nair 2004; Datta et al. 2017). This reduces the atmospheric C which would otherwise be released into the atmosphere by cutting more forest for farmland or pasture. AFS can be a sink or a source depending on the land-use system that it replaces. If they replace natural primary or secondary forest, they will accumulate lower biomass and C, but if they are established on degraded or treeless land, their C sequestration value will be considerably increased. The clearing of primary forest releases more C than natural regrowth or fast-growing plantations could recover in 25 years or more. Therefore, protection of primary forest should be a top priority when looking at ways to reduce C emission.

AFS are recognized to have the potential to regain some of the C lost to the atmosphere in the clearing of primary or secondary forests, although neither regrowth nor plantations can come close to replacing the full amount of C that was present in the primary forest (Montagnini and Nair 2004).

(g) *Alley Farming*

Alley cropping is an AFS practice, also known as intercropping, which is applied to sequester C trees and soil from the atmosphere. This method is very similar to HI, and in the tropics no distinction is made between the two (Albrecht and Kandji 2003). The practice involves rows of crops cultivated alongside rows of trees. Trees are planted in rows, and the alley ways in between the rows of trees serve as bed for agricultural crops. Most types of horticultural and agricultural crops can be grown in this manner.

The system could be planted in single or multispecies trees, grass and shrub in rows with agronomic crops or pasture grass grown in the alley. Expected benefits of alley cropping include improvement in environmental quality, economic returns, C sequestration and wildlife benefits (Koskela 2000). In alley cropping, spatial heterogeneity exists in C stock and sequestration due to factors such as tree and crop row configuration, differences in C input into the soil, decomposition rate and previous management and associated soil microfauna (Mann 2016; Udawatta et al. 2008; Montagnini and Nair 2004).

Three main components that can influence the utilization of environment by species in alley cropping include space, resources and time (Peich et al. 2006). Species utilizing the same exact combination of these resources as another will be in direct competition which could lead to a reduction in C sequestration. However, if species differ in utilization of even one of the components such as light saturation of C3 vs. C4 plants, C sequestration will be maximally enhanced (Udawatta and Jose 2011).

Most AFS and practices harbour the potential to sequester C if managed properly taking into consideration the factors that have been seen to influence above- and belowground C sequestration. This suggests that with adequate management, a significant fraction of atmospheric C can be captured and stored in plant biomass and in soil (Montagnini and Nair 2004). Agroforestry C sequestration can be used to reduce atmospheric C in different parts of the globe. Udawatta and Jose (2011) indicated possible net gains in C sequestration that could be used to promote agroforestry as a promising C mitigation strategy in the USA and potentially in other parts of North America. A 4.7 Tg CSP for riparian buffer, 60.9TgC year^{-1} for alley cropping, 474 TgC year^{-1} for silvopastoral and 8.79 TgC year^{-1} for windbreaks. The total C that could be sequestered in the USA according to their study is 548.4 Tg year^{-1}.

This could offset the USA CO_2 emission by 34%. In Africa, although for many parts adequate investigation has not been carried out, many studies showed good estimates of aboveground C accumulation in agroforestry (Ajayi et al. 2011; Dupe et al. 2011; Meena et al. 2016a). In the humid tropics, Mutuo et al. (2005) also reported great potential for agroforestry in the reduction of atmospheric C.

Soil C levels can be increased considerably at a global scale by agroforestry practices, thereby reducing atmospheric C. Soils have a finite sink capacity of 0.4–0.6 PgC per year over 50–100 years (Paustain et al. 2000). If aboveground and belowground soil C are considered together, 1.1–2.2 PC could be sequestered annually over 50 years using agroforestry practice.

This according to Dixon (1995) will offset about 10–15% of annual C emission, thus contributing to CO_2 reduction. The IPCC report estimated that the area currently under agroforestry worldwide is 400 million hectares with an estimated C gain of 0.72 Mg C ha year^{-1}, with potential for sequestering 26 Tg C year^{-1} in 2010 and 45 Tg C year^{-1} by 2040 (1Tg = 1012 g or one million tons). This will help a lot in the reduction of atmospheric C (Watson et al. 2000).

The analysis of C stocks from various parts of the world showed significant quantities of C (1.1–2.2 Pg) and could be removed from the atmosphere over the next 50 years if AFS are implemented on a global scale (Albrecht and Kandji 2003). Nevertheless, unguarded practices are threats to the promotion of agroforestry and forestry. Therefore, a conservative option like afforestation is needful in replacing degraded lands and forest areas.

8 Afforestation as a Sustainable Option in Regaining Forest Losses for Possible Climate Change Mitigation

Afforestation is the growth of forests or planting of trees in an area where there was no previous tree cover or previously not classified as forest. It is the process of planting trees, or sowing seeds, in a land devoid of trees to create a forest (Li et al. 2012). This differs from reforestation, which is the process of planting trees into a forest that has decreasing numbers of trees. Reforestation is increasing the number of trees in an existing forest or the creation of a new forest. However, both practices are deliberate efforts to promote the development of forests. Afforestation could have a number of purposes. It is practised in many places and establishes a high C land use (Laganiere et al. 2010). It produces economic trees of high importance and helps reduce pressure on existing forests. Through afforestation, trees are cultivated on degraded agricultural lands and other lands destroyed by resource exploration like mining and quarrying.

Human population has over the years created damage to forests, resulting into global warming and climate change. Communities use forest resources, clear forest lands, cut trees and in the process create more environmental problems like air pollution and land degradation. Timber and food production have created huge damages on existing global forests. The global forests have been enormously depleted. Therefore, urgent sustainable measures are required to replenish them. In such degraded areas, afforestation has become a feasible option. Today the focus of forestry is wide, in recognition of a broad range of ecosystem services from forests. In some countries new forests are used to replace annual cropping on active croplands and degraded grassland. Afforestation aims to provide an alternative source of timber and to reduce emissions arising from deforestation. This is to reduce the pressure on existing hardwood species in forests.

Recently, climate mitigation is pursued through bio-sequestration in biomass and timbers. With the recent environmental concern on global warming, the reduction of GHG through the forests has attracted attention of policymakers (Lal 2005). Afforestation of degraded lands represents a sustainable land use that sequesters C (Khamzina et al. 2012). Studies show that sequestration accounts for 10–50% of emissions reductions globally in a cost-efficient climate policy (Murray et al. 2009; Sohngen 2009).

For lasting impacts, the European Commission (2011) has proposed a means to provide a competitive, low-C economy by 2050. This approach proposes reductions in GHG up to 80–95% by 2050 compared with the level in 1990. Today, many governments and organizations are engaging in afforestation programmes to create and conserve forests to increase C sequestration and improve biodiversity. Afforestation is therefore of critical importance for mitigation and restoration of degraded lands and hence climate change resilience (Akanwa et al. 2017).

The introduction of forestry practices on degraded lands can be an effective land-use practice that could increase food supply, reduce poverty and improve the environment (UNEP 2011). Diversifying farming activities through afforestation could reduce the impacts of agricultural risks by providing a variety of products to farmers (Baumgärtner and Quaas 2010). Despite the environmental and economic attractiveness of tree planting on marginal croplands, such land use is not commonly practised in Africa.

Tree plantation can be an effective long-term land-use investment although it is constrained by land tenure and uncertainty in returns (Kan et al. 2008). Hence, flexibility in land-use policies may increase attractiveness of afforestation.

Moreover, afforestation of marginal lands is a new land-use practice, where farmers are yet to fully take advantage of its possible benefits, costs and management practices that would generally impact their wellbeing (Kan et al. 2008).

8.1 Protected Areas (PAs)

PAs are natural or created habitats that are legally protected in order to preserve their ecological, cultural and biological functions. The increased negative human impact on forests has created attention for nations to take conservation and maximization of the diversity of plant and animal species among others seriously. PAs may include wetlands, riparian habitats and forests. Wetlands contain areas of high biodiversity that can offer a range of environmental services. Rural greening programmes should embrace all the benefits of PAs through preserving existing areas, expanding existing areas and creating new ones. These areas serve as sanctuaries for local animal species while providing access for recreation or other related uses.

8.2 Greening Urban Areas

The concept of urban greening is fast becoming an attraction. It is an integrated approach of tree, vegetation plantation and management in an urban area to derive multiple environmental and social benefits for people (Miller 1988). Urban greening contributes to making cities more liveable and sustainable. The two indicators that measure the level of urban greening are share of green urban areas and distribution of green urban areas. The share of green urban area is the proportion of vegetated areas within the city boundaries in relation to the total area, while the distribution of green urban areas is the relationship between green area boundaries and all the other elements present in the city. An uneven distribution of green urban areas implies unequal accessibility for all city dwellers. The various types of urban green space are as follows:

(a) Public parks: A public park represents one of the most visible and popular components of an urban greening programme. Depending on its accessibility, variety of services and management, parks attract people for recreational purposes. Urban parks located within living premises like a neighbourhood can increase the quality of life for the people by providing opportunities for leisure activities. It also provides a range of environmental services, depending on its size and design (Kuchelmeister 1993). Parks with extensively forested areas can provide animal habitats and plant species.
(b) Street and residential trees: There are a number of multiple benefits associated with trees planted along urban streets. Street trees beautify a city and provide a range of environmental services. In cities trees provide fruits and other tangible benefits to people. People derive firewood, natural shading and mulching material from urban trees (Kuchelmeister 1991). The use of species that have such economic benefits can encourage urban residents to take an active role in the maintenance of the trees.
(c) Urban agriculture: Urban agriculture activities include fish farming, market gardening, micro-livestock and poultry production, flower beds, orchards, managing tree nurseries and field crops. Agriculture occupies more a considerable proportion of green uses in urban land. Cities can have family garden programmes as part of their urban greening system. Urban agriculture can be integrated into other urban greening components.
(d) Greenbelts and greenways: Greenbelts are large parcels of undeveloped lands in and around cities where urban development is totally prohibited through planning regulations (Miller 1993). Greenways are often sited along rivers, ravines, ridgelines and floodplains that cannot be built on due to environmental and physical limitations. As narrow-vegetated corridors, they can have multiple uses and functions. These functions and uses include cushioning urban congestion and pollution, environmental quality, providing recreation and serving as alternative transportation routes (bicycle and foot paths).
(e) Watersheds and protected urban Areas: Watershed management is a major component of urban greening. This usually has trees along riverbanks and within the

watershed areas. City planners need to work with other stakeholders with vested interest in watershed areas to ensure adequate protection of this important resource. Urban areas should also be included in a region's system of PAs. Many urban areas have areas like ravines, riversides, watersheds or steep slopes that are unsuitable for development but should be protected.

8.3 Advantages and Disadvantages of Afforestation

Assessment of benefits of forest plantations has shifted from consideration of only production of timber to multiple ecosystem services. Afforestation has both direct and indirect effects on community livelihoods. Many studies identified the multiple benefits of tree plantations including food, timber and environmental services provided by trees. Croitoru (2007) estimated that the annual returns from multiple non-timber products alone such as fuelwood, cork, fodder, honey and mushrooms constitute about a quarter of the total value of forests. Studies on the impact on rural livelihoods and ecology identified its contribution to sustainable development in terms of agricultural diversification (Stringer and Dougill 2013; Painkra et al. 2016).

The advantages of afforestation include the following:

1. Production of fruits for consumption and leaves for livestock fodder.
2. Production of trees that provide wildlife habitats. The trees serve as home, safe dwellings and food source for animal species. It therefore promotes increased biodiversity level.
3. Increase in the supply of timber and charcoal. It supplies fuel for cooking and heating and wood for poles, timber, paper pulp and other commercial uses (Khamzina et al. 2012).
4. By producing these resources, it serves as a basis for development of local entrepreneurial opportunities. Job opportunities are created, and income is generated for local businesses.
5. It helps in climate change mitigation. Trees play an important role in minimizing the greenhouse effect. Storing C through forests is considered a cheap means to decrease emissions.
6. Sequestering C in forests can generate additional benefits for farmers through the CDM afforestation and reforestation projects. This is the recent global source of forest C credits, accounting for 50% of the forest C market value (Hamilton et al. 2010).
7. Additional ecosystem services from tree plantations include land rehabilitation, increase in soil nutrient stocks and irrigation water saving (Khamzina et al. 2012).
8. Trees and their roots have a significant role in binding soil together and preventing erosion.
9. It reduces pressure on natural forests, i.e. serve as alternative sources for forest products.

10. Forests contribute to urban and rural landscape aesthetic values and outdoor recreation.

While afforestation offers a lot of benefits to both the environment and society, there are arguments that it can also bring some drawbacks which include the following:

1. The transformed lands can no longer be used for other human services and activities particularly agriculture for food supply; thus it comes with real opportunity costs.
2. If not properly managed, afforestation can result in reduction of biodiversity in the local ecosystem, introduction of potentially invasive species and modification of existing biome.
3. Afforestation can be informed of monoculture that lacks plant diversity and good habitats for some animal species.
4. Afforestation for the purpose of ecotourism can be associated with some problems including discomfort to wildlife.

Despite the environmental and economic attractiveness of farm forestry, such land use is not currently common in developing many countries. Investment on such long-term land use as forest is constrained by land tenure system, and uncertainty over time affects farmers' interest (Castro et al. 2013; Djanibekov et al. 2012; Varma et al. 2017). Moreover, as a new land-use practice to farmers, they lack knowledge of its possible benefits and costs, as well as management practices and general impact on their livelihood (Kan et al. 2008). Despite the various benefits of afforestation, farmers' perception remains a vital factor that affects the adoption of the land use (Djanibekov et al. 2012). Therefore, in implementing afforestation, it is necessary for farmers to understand the multidimensional effects on rural livelihoods. Unfortunately, there are number of human activities responsible for forest losses and changes.

9 Human Activities Responsible for Global Forest Losses/Reduction

Forests sustain livelihoods, help to control flooding, recharge aquifers, pollinate crops, cycle nutrients, harbour biodiversity and sequester C. As a result, forest loss and degradation have serious environmental and socio-economic consequences. The Forest Resources Assessments from 1980, 1990, 2000 to 2005 by the Food and Agriculture Organization showed rapid change in forest cover globally through deforestation, and a number of factors are identified as being responsible for this situation (FAO 2005; Akanwa and Ikegbunam 2017b; Akanwa and Ezeomodo 2018). Unsustainable land-use practices are major causes of global forest reduction (Turner et al. 2007); these practices including mining of natural resources, farming and timber harvesting are major mechanisms of deforestation (Akanwa et al. 2017; Akanwa and Ikegbunam 2017a).

Rural communities depend mainly on agriculture. At present, about half of arable lands are experiencing degradation. Degraded lands reduce agricultural production and costs about 400 billion USD annually on a global scale, thus affecting 1.5 billion people (Lal 1998; Bai et al. 2008). With irrigation there has been some improvement in land productivity, but in this agricultural system, croplands experience degradation due to excessive waterlogging (UNEP 2009). In recent years, irrigated agriculture is further affected by temperature increase arising from climate change (Lioubimtseva et al. 2005) and related reduction in water resources for irrigation. This situation threatens agricultural production and the livelihoods of rural population.

Some studies showed that returns from crop production on marginal croplands are increasingly reducing (Niu and Duiker 2006). Though, several options were proven to offer quick land improvement to boost production while contributing to climate change mitigation and improvement of rural welfare, there are few incentives to apply such options (Bobojonov 2009) as they require high costs and technologies not within the reach of some countries. Therefore, better options for land-use practices like afforestation are required to cope with these challenges (Khamzina et al. 2012). The introduction of forestry practice on farmlands is an effective land-use practice that could improve food production and reduce poverty (UNEP 2011).

Afforestation of marginal croplands can combat land degradation, diversify farmland use and buffer against agricultural production risks via replenishing nutrient stocks (Khamzina et al. 2012). C sequestration through afforestation is seen as environmentally, economically, politically and technically feasible for fighting global warming.

9.1 Improvements in Afforestation

There are various types of afforestation practices that include seeding dense plots of diverse indigenous species and the introduction of single species as a plantation. Afforestation projects can be in the form of native forest restoration, timber plantation or agroforests/multipurpose trees. Afforestation projects in the form of plantations are on the rise globally, with trees planted for timber, fibre and C offsets. Recently, fast-growing native species are developed to achieve multipurpose forest services including enhancing biodiversity; meeting human needs for firewood, food and medicine; and providing ecosystem services such as flood and drought control (Paustian et al. 1997).

For example, bamboo is a plant that is cultivated for many uses, from buildings to food and to paper. Bamboo is planted on about 77 million acres today and estimated grown on an additional 37 million acres of degraded or abandoned lands (Conservation Institute 2014). Bamboo rapidly sequesters C in biomass and soil, taking it out of the air faster than almost any other plant, and can thrive on inhospitable degraded lands. It reaches its full height in a short time and becomes due for harvesting for pulp or allowed to grow to maturity in 4 years. After harvest, it resprouts easily and grows again. An initial bamboo investment of $24 billion could yield a 30-year financial return of $265 billion. The C sequestration calculations both living biomass and long-lived bamboo products are at an annual rate of 2.9 tons of C per acre. Where bamboo is substituted for aluminium, concrete, plastic or steel, emissions can be avoided to the atmosphere.

Some other tree species have high potential to grow on marginal croplands. These include native tree species with high tolerance to local environment and can serve in agroforestry. Agroforestry provides timber, fruit and fodder for cattle; prevents soil erosion; enables better retention of water; and shields crops from excessive wind and sun damage.

9.2 Solution to the Challenges to the Forest Sector

I. Funding: More funds are required for forestry development. Nontraditional sources of funds such as fund from NGOs and the private sector can be exploited. The subnational levels of government particularly in the developing countries should show more commitment to afforestation programmes. They should make efforts to sustain the gains of afforestation by ensuring that the salient principles are imbedded in forestry planning and management. This may include plantation establishment and encouragement of local communities in agroforestry. Forestry departments should embark on intensive awareness campaign and public enlightenment on the importance and benefits of forests. Community participation in forestry programmes should go beyond enlisting their support to making them part of the planning and management of forest resources. The private sector should be further encouraged in afforestation development through creation of enabling environment. There is the need to address the land tenure challenge with particular reference to empowering the private sector to have easier access to land to develop forests. The agencies should anchor on the existing funds from international agencies and donors for afforestation projects.

II. Forest conservation: This is the deliberate management of forests in order to protect the habitat and natural resources. Forests provide man with various products and benefits such as wood, fruits, nuts, dyes, medicines, gums, climate change mitigation, erosion control and habitat for biodiversity. But rainforests have over the years been affected by human impacts, climate change and the devastating effects of natural disasters. Annually, millions of hectares of the world's rainforests are lost, mainly to logging, slash and burn farming and advance of agricultural and cattle herding frontiers. In 1992, the Earth Summit in Rio de Janeiro raised concern over the global environmental degradation and the need to protect biodiversity. The Summit drew attention to the rampant deforestation and threat to the world's forests. Accordingly, the Brundtland Commission Report called for sustainable development and greater commitment towards protecting the ecosystems were considered. In an attempt to address the situation, 150 governments signed the Convention on Biological Diversity (CBD) agreeing to set up a system of PAs or areas where special measures need to be taken to conserve biological diversity. Forests, especially tropical forests, are the most threatened natural spaces and are included in the UNESCO List of World Heritage in Danger. In 2001, the World Heritage Committee adopted a specific policy to preserve forests, and over 107 forest sites covering a total of 75 million hectares across the world have been listed in the UNESCO World Heritage.

The Sustainable Development Goals (SDGs) also placed importance on the harmonization of the economic, social and environmental dimensions of sustainability – with focus on the conservation and sustainable development efforts in the tropical forest biomes. Three of the 17 sustainable development goals relate directly to the forest biomes as follow:

1. Goal 12: Ensure sustainable consumption and production patterns.
2. Goal 13: Take urgent action to combat climate change and its impacts.
3. Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss.

During the 2003 International Union for Conservation of Nature (IUCN) conference in South Africa, governments of countries pledged to increase their PAs. As a follow-up, for example, PAs in Madagascar increased from 1.7 million hectare (M ha) in 2003 to 6.0 million ha in 2009 (Green Synergy 2009) and to 7.2 M ha in 2010 (SAPM 2010). Large parts of the new PAs served as C sinks to mitigate the effects of climate change. During the 13th session of the Conference of the Parties (COP 13) of the UNFCCC in Bali in 2007, the reducing emission from deforestation and forest degradation (REDD) initiative was recognized as a feasible mechanism for forest conservation to fight against climate change.

This is to encourage developing countries to conserve their forests. Some government funds, such as the Australian Forest and Climate Initiative and the Norwegian Government Fund, were established to support the REDD activities. The World Bank also recognized the REDD as a priority tool in forest conservation and initiated its Forest Carbon Partnership Facility (Green Synergy 2009).

Despite the considerable increase in PAs across the globe (IUCN 1998), deforestation still remains a serious challenge as emissions from deforestation and forest degradation remain responsible for an estimated 12–18% of global C emissions (Stern 2006; Van Der Werf et al. 2009; Kumar et al. 2017). Several other steps were taken by governments and NGOs to implement the REDD at the local levels.

The global meeting on the 'Frameworks for Tropical Forest Conservation' also provided an international interactive forum for knowledge sharing and synthesis on tropical forest conservation and sustainable development. The specific objectives include dissemination of environmental policies on conservation and sustainable development in tropical forest regions; hence, developing a preliminary framework that would harmonize the environmental, social and economic dimensions towards conserving tropical forest and further would act as a model for emulation at international level with regard to applicability, adaptability and implementation.

While these global treaties, regulations and strategies are important, cultural identity is the key to conservation of forests. The rainforests are the livelihood of over one billion of the world's inhabitants whose activities and use of the forest needs to be regulated. Therefore, the conservation of the rainforest requires anthropological and sociological balance with the communities who live within the rainforests. Governments and civil society will have to multiply efforts in meeting with their responsibilities of protecting rainforests.

10 Environmental Greening an Innovative Tool for Climate Change Mitigation

Greening rural and urban environment is an important tool for resource protection, landscape design and aesthetics and improving socio-economic welfare. The rural population depends directly on the environment for agricultural activities, forest products and exploration of natural resources among others (ILO 2014). The environment is placed under pressure to provide these services; thereby natural resources such as water, air, plants, animals, vegetation cover, soil, etc. are increasingly threatened by excessive use. Hence, environmental changes caused by climate change become unavoidable.

These rural communities, however, are poor without adequate social protection and environmental awareness and thus bear the highest costs of environmental degradation.

The main consequence is the increasing risks to rural livelihoods. The preservation and enhancement of a green system can improve the quality of life by safeguarding the quality of environment and its natural resources.

Green spaces in urban and rural areas can provide people with direct access to economic benefits through agriculture or forestry. Careful planning is the key to ensure that settlements have healthy green environment. This means putting in place methods and processes for landscaping and design, green spaces, recreation, parks and open spaces with sustainable management strategies to enjoy the benefits within. The general standard established by the World Health Organization is a minimum of 9 square metres of green space per city dweller. Currently, most urban areas do not have such green area per person.

10.1 Greening the Rural Areas

The rural areas heavily depend on agriculture. At present, most arable lands in rural areas are experiencing degradation, leading to lower agricultural production. This problem has implications on the livelihoods of rural population. It is given that globally agricultural production is affected with 400 billion USD lost annually and 1.5 billion people's livelihoods were affected (Lal 2005; Bai et al. 2008).

Addressing this issue requires policy interventions that could be the engine for a sustainable environmental and economic transformation on rural economies. The ILO (2014) in this green job project suggested that rural economies should be empowered through access to clean energy; introducing sustainable farming methods; fostering sustainable tourism; restoring degraded ecosystems; income diversification; environmental protection; and stimulating social dialogue for an effective, inclusive and productive transition to sustainable economies. Green jobs can reduce negative environmental impacts, thereby leading to sustainable economies that are environmentally, economically and socially viable. Approaches to achieve rural greening include the following:

10.2 Greening Peri-Urban Areas in the Urban-Rural Interface

The urban-rural interface is the space where a city or town meets the rural area. It is a dynamic and highly diverse zone, where development processes and changes occur at different scales. Here, there is a high competition for land among many land uses; thus the area experiences high level of encroachment of development into green landscapes leading to loss of ecosystem services and functions. In this peri-urban transition zone, two key issues of concern are effectiveness of green infrastructure and competition for space. Green infrastructure in this zone performs similar ecosystem services to that in inner urban areas such as forming ventilation channels, alleviating the urban heat island effect and facilitating the circulation of fresher and cleaner air from the periphery into the city.

10.3 Benefits of Greening Urban and Rural Areas

Green spaces provide various services such as provisioning services, regulating services, supporting services, cultural services and recreational services (Ong 2003; Dobson et al. 1997). As presented in Table 2, they can be classified into direct and indirect benefits.

10.4 Planning Green Spaces

Cilliers (2015) noted the importance of planning for green spaces in local communities, especially in a rural context, where complexities regarding value of space are perceived differently, depending on the challenges and needs. The necessary factors to consider in planning green spaces include the following:

Table 2 The benefits of green space provision

Benefits		Measurable
Indirect benefits	Environmental benefits	Ecosystem services, enhanced biodiversity, habitat provision, storm water management, reduced CO_2, improved air quality, reduced pollution, microclimate and heat island effect, noise reduction, sustainability
	Social benefits	Leisure and recreation, social contact, access to experience physical and psychological health, aesthetic value, quality living space, positive perceptions, community cohesion, levels of physical activity, reduced stress, increase happiness, positive impact on children, lower levels of fear, better neighbourhood relationships
Direct benefits	Economic benefits	Favourable image of place, boost retail sales and tourism, inward investment in area, encouraged employment, property values, neighbourhood value, house buyers preferences, positive influence in crime areas, development impact on children

(a) Understanding green space – An important issue is creating clear understanding of green spaces in terms of their influence, the benefits of green spaces and the importance of driving the sustainable development goals. Qualitative green spaces provide varied functions to communities, including health, social, ecological and economic services.
(b) Approaches to planning green spaces – Current planning approach is often project oriented and rarely supports green growth. There is the need for an inclusive approach which considers community participation in green space planning.
(c) Valuing green spaces – The value of green spaces needs to be identified in order to emphasize the importance of planning for such spaces.
(d) Quantitative targets – When designing a city's green space infrastructure, planners should aim to fulfil certain quantitative targets. The World Health Organization (WHO) recommends that cities provide $9m^2$ of unpaved open space for every inhabitant and design green area networks so that all residents live within a 15-min walk of an open space.
(e) Maximizing use and benefits – Planners need to design urban green areas in a way that maximizes their potential uses. Whereas urban green areas have been traditionally designed for recreation and aesthetic value, their usefulness far exceeds these functions. With proper design, green areas can also maximize diversified benefits.
(f) Integrating greening into other improvement projects – Greening can be integrated into projects beyond the traditional contexts of city parks, street trees or greenways. For example, planners can integrate green areas into highway construction, flood plain protection, urban farms, transportation and housing programmes. The additional benefits of integrating green areas into other projects are mainly due to most of the costs are absorbed into the budgets of the projects.
(g) Maintenance – Planners must think about maintenance, protection and monitoring. A safe, well-maintained green area provides multiple benefits for the surrounding community; hence, the plan should be able to stimulate citizen participation towards upkeeping of the area.

(h) Multiple sources of financing – The plan should include strategies for funding the project. This may require multiple sources of financing with strong participation of the private sector and other NGOs.

10.5 Challenges to Greening Urban and Rural Areas

There are several recurrent obstacles that stand in the way of the planning and execution of green areas in rural and urban landscapes. The major challenges include:

1. Valuing the real benefits – Some benefits of greening are not measurable in monetary terms, and thus are not visible to investors and the general public and difficult to include when making investment decisions.
2. Institutional capability – Greening is an integrated process that requires an exceptional level of institutional capacity building that would enable planning, execution and maintenance of green areas. Often it required capacity through appropriate technology and skill.
3. Public participation – An important challenge is how to maximize public participation and support at all stages of the project. The public can contribute ideas or resources towards the project.
4. Financial sustainability – Securing funds for greening projects can be a difficult task in developing countries where pressing issues seem to be given more attention. It is often overlooked, and hence, funding for regular maintenance and protection of green spaces is hardly available.
5. Land tenure – Means of accessing lands are usually difficult since lands are owned by either the state or an individual or they are open access. Lands privately owned also have limited access and are difficult to obtain for such purposes.
6. Ecological constraints – There are a number of practical constraints towards greening the environment. These include concrete pavements in city commercial areas and densely populated areas that need to be removed for plantation purpose. Urban planting sites are often unhelpful to some species due to air and land pollution and low water table that can make plant susceptible to injuries caused by traffic and human movement (Center for Landscape Research 1993). These factors affect survival of plants.
7. Legislation – Urban greening is relatively a new concept without legal support and enforcement especially in developing countries. Most city ordinances and protective laws did not cover urban greening.
8. Management of green areas in informal settlements – In green spaces located close or adjacent to scattered settlements, there is usually environmental pressure on these green areas where activities like dumping of wastes, trampling of plants and cutting of trees for firewood are rampant.
9. Uncontrolled urban growth can lead to encroachment into open spaces in unplanned, fragile areas such as steep slopes, riparian corridors, flood plains and watersheds.

10. Management interdependence – The jurisdiction over regulation of such environmental factors as land, surface water and park management usually do not fit into one agency. There is a need for cooperation among agencies in order to avoid conflicts and competition for funds and authority.
11. Local rural/urban realities and social challenges – Rural communities usually experience low employment and high poverty levels. Organized green space is not a priority to them. In urban areas, bad perceptions regarding safety and security in green spaces make people to avoid open spaces.

10.6 Basic Requirements for Developing Greening Project

(a) Type of project – There are three principal investment designs for greening programmes, though it depends on the number and size of the settlement involved and on the priority of greening among project options. They are individual self-sustaining projects, multiple works projects and subcomponent projects. Individual project means having greening as a single investment project for a city. Multiple works projects involve urban greening for more than one city or region at a time. As a component of integrated city projects, urban greening can be accomplished. For example, such greening can be incorporated into a flood control project.

(b) Training and information exchange – Essential to greening is the provision of adequate technical assistance in the form of training, extension services and capacity building for urban forestry, agriculture, tree care and park upkeep for workers and staff. People who are responsible for handling the various components of the system may lack the skills needed for their new responsibilities. Training such persons to meet their professional duties will greatly contribute towards successful implementation of greening projects.

(c) Environmental education/awareness – Much of the success of greening project depends on public participation; thus it is crucial to inform people on the significance of the project. Where the public is required to maintain green spaces, they have to know how to carry out their responsibilities.

(d) Institutional strengthening – Building local institutional capacity is required to develop the technical and management elements needed to sustain greening efforts.

(e) Maps – Map is one of the effective tools for managing, monitoring and doing inventories of green space resources. Maps provide pictorial representations of the existing resources, landscape, transportation routes, topographic and soil profiles, and man-made structures and the zoning provision. Geographic information system is computerized mapping systems that digitally display natural or man-made geographic features on a map.

(f) Political support – By integrating urban greening into the state and national environmental plans and performing follow-up evaluations, a central government can monitor progress made in greening programme in the country (Lampietti and Subramanian 1995). This can also influence political decisions regarding the type of urban greening to be implemented.

(g) Flexible practice – Some regulations should allow for flexibility. For example, in Curitiba, Brazil, developers can exceed zoning limits on building height by trading vertical space for green space.
(h) Regulatory law and its enforcement – Urban greening needs to fit into the existing legal framework to have legal support and protection against competitive uses and destruction. The enforcement of the law is also important to guide against violators.
(i) Technical viability and environmental sustainability – The technical viability of a greening programme depends on the capacity to properly site, construct, maintain and monitor a green space in a way that ensures a continuous supply of the intended benefits. In any green space, preserving plant and animal species requires knowledge of the various species' needs and sensitivities to implement and monitor and undertake the requisite remediation when necessary.
(j) Financial and economic viability – The two principal determinants for the economic viability of a greening project are financial rate of return to investors and socio-economic benefits to the public. It is therefore crucial to calculate the economic benefits of a green project relative to the cost.

11 Conclusion

This book chapter reviewed environment-friendly strategies for minimizing the global consequences of climate change. In recent times, the accumulated human activities over the years have released toxic pollutants into the atmosphere releasing hydrocarbons which contribute to the greenhouse effect and, hence, global warming and resultant climate change consequences. Sustainable measures such as reformation of environmental policies covering industrial gaseous emissions and agroforestry application in rural and urban areas. The practical applications include agriculture, alley farming, tree planting with attention to tree species and forestry practices that are less vulnerable to storms and fires; effective mitigation policies and utilizing new technologies and new agricultural practices among others were suggested in this chapter.

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Radioecology and Substance Interaction with Nature

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Abstract

Radioactive substances have their origin since the inception of earth. The warming of earth surface still takes place through radioactive disintegration of radionuclides (Rn). Rn may often pose danger to human civilization due to their environmental fate. Proper knowledge regarding the origin, distribution, exposure and impact of radioactive substances has become the need of the hour in the form of radioecology. Among the 340 atoms of different naturally occurring nuclides, 70 species are radioactive substances. These substances are found throughout the environment including the human body. Human and other living organisms are often exposed to various levels of Rn through background concentration as well as through artificial radioactivity. It was observed that the growth of science and technology has made living organisms more vulnerable towards environmental radioactivity. Various historic events have taken place which created the urgency to have knowledge in radioecology. After the incidence of Chernobyl in 1986, an area of more than 4500 km^2 was contaminated through various Rn. The impact of Rn was visualized at various levels and types of ecosystem as revealed from the Fukushima and Chernobyl disaster incidence. Hazards of radiation have necessitated to generate a baseline data of radioecological impacts on ecosystem. As per Spiers radium-226 is the most prevalent radioactive particle, and its value was 2.6–2.7, 0.2–0.3, 0.8–1.6, 1.3–1.7, 2.4–3.3, 0.8, 3.1–3.7, 0.9 and 0.6–0.9 picocuries per kilogram in various food commodities such as bread, milk, potato (*Solanum tuberosum*), vegetables, root vegetables, rice (*Oryza sativa*), eggs, fish and fresh meat. Originally, mobilization of Rn along with their impacts on various components of the environment becomes the central theme of radioecological studies. For safety and risk reduction, proper management of natural and artificial radioactivity is the essential prerequisite. For effective management, data should be procured through field-level studies as was revealed from Fukushima and Chernobyl incidents. Policy formulation and strategy buildup are required to address the issues of radiation hazards, and their adaptive measures through reducing the risk of exposure and overall public awareness are the most important aspect. Future research should be promoted in order to propagate the knowledge built within radioecological perspectives.

Keywords

Food chain · Radionuclides · Radioecology · Trophic level

Abbreviations

C	Carbon
CS	Caesium
CF	Concentration factor
DNA	Deoxyribonucleic acid
K	Potassium

NPP	Nuclear power plant
OPRI	Office de protection contre les rayonnements ionisants
RC	Radiocaesium
Rn	Radionuclides
Sr	Strontium
TF	Transfer factor

1 Radioecology: An Introductory Remark

Radioecology addresses the environmental presence of radionuclides (Rn) and their traces, origin and mobility and accumulation in the ecosphere. Broadly we can divide the radioecological impact as environmental impact of natural and artificial radioactivity and dosimetric impact, i.e. impact on population. Such studies are mediated in the same way as for the pollutants and toxicants. The complex transfer process within the ecosystem was studied by the scientists in marine ecosystem, inland aquatic ecosystem and land ecosystem. Rn remain scattered in water and air and subsequently settle in soil and sediments, move further through the food chain and reflect negative impact on human health. As per research reports, the Fukushima incident promoted radioactive exposure through caesium (CS)-137 (half-life of 30.1 years) with a higher affinity towards soil particles (Okumura et al. 2018).

Abiotic and biotic components that frame the biosphere are distributed into different units named ecosystems. Examples include forest, pond, lake, mountain and desert through which Rn circulates among these different ecosystems. Radioecological concepts deal with the measurement of the concentration of Rn and their further migrating mechanisms. Radioecological studies provide raw database for assessing the impact of radioactivity in population (dosimetric impact). Radioecology also addresses issues related to nuclear power plant (NPP), radioactive waste, public health hazards, etc. (Moller and Mousseau 2017; Dhakal et al. 2016).

Radioecology has its origin during 1935 but has been widely recognized since 1950. It harnesses two major disciplines, radioactivity and ecology. The first report of radioecological event took place in the international meeting for evaluating nuclear energy use in 1955 at the Pacific region. Some of the major events of radioecology include testing of nuclear weapons in France, ZOE reactor divergence, Hiroshima and Nagasaki bombing and framing ecological intervention through the construction of ecological groups. Two major organizations involved in radioecological work include in France ISPN and OPRI (Office de protection contre les rayonnements ionisants). ISPN aims to work for protecting the environment in various sites throughout the world. ISPN themes include radioecological exploration in the Atlantic seaboard, environmental modelling of radioecological migration, studies related to radon and atmospheric contaminants and research studies in the Mediterranean region. OPRI represents supervision and regulatory activities related to radioactivity present in the environment. It also acts as a networking system which prepares the working plan in relation to emergency preparedness due to abnormal radioactivity in France.

Ecosystems are a very important part from a radioecological point of view. Ecosystem is the raw resource based for all the living biota on the planet earth. It provides food and water and overall acts as substrate media for survivability of plant, animal and microorganisms (Raj et al. 2018a, b). If we trace the radioecological impact at different trophic levels of the ecosystem, it would be surprising to note that the overall consequences would inhibit or alter the main ecological function of ecosystems. The level of Rn variability in different vegetal parts significantly influences the mobilization of Rn from plants to animals. On the contrary precipitation mediates much more mobilization of the Rn in the ecosystem. In terms of ecological interaction, radiation also influences various forms of biotic and abiotic interactions present in the ecosystem (Moller et al. 2012).

The present chapter deals with radioecological framework from ecological and environmental perspective to generate an awareness about radioecological impact and its mitigatory policies.

2 Radioactivity and Environment

Humans are frequently exposed to radioactivity in terms of background radiation as well as artificial radioactivity. Such radioactive elements are frequently found in the environment, and their existence has been located even in the human body.

Artificial radioactivity occurred during the nuclear weapon test, and nuclear explosions lead to the release of radioactive substances such as CS-137, ruthenium-106, strontium-90, tritium, etc. in the upper atmospheric zone and then subsequently settled down in the oceans and the land surfaces (Table 1). It has been estimated that such explosions have released 500 times of Rn in the environment as it was released during Chernobyl disaster. Satellite fall is another important event for spreading radioactivity in the environment. As per the earlier reports, the re-entry of satellites in the atmosphere has released plutonium-238 which even reached the French territory in trace amount.

Rn contamination in leaves usually takes place through rainfall or high wind flow. After initial contamination in leaves, Rn migrates towards the earth followed by root migration. Mosses and lichens are used as principal bioindicators. Subsequently animals get contaminated through plant ingestion. Rn follows the typical pathway from producer, primary consumer and then secondary consumer. There is a significant level of variation in the impacts of atmospheric pollution on seasonal basis as Rn settle both under variable conditions in cultivated and uncultivated area. The impact may be reflected on seedlings or in the case of mature vegetation. The mechanism of transfer of Rn can be well studied through transferring one earth block from the natural earth surface and transferring it into laboratory under controlled climatic condition. Various cultures in the form of beans, corn and vines may come under contamination at various growth stages. In case of NPP, the

Table 1 Radioactive substances within the environment

Environmental components	References
Biosphere	
Radium-226 is the most prevalent radioactive particle, and its value was 0·85 × 10^{-14} g Ra/g in bone ash of human in Bombay and Kerala, India	Chhabra (1966)
Radium-226 is the most prevalent radioactive particle, and its value is 2.6–2.7, 0.2–0.3, 0.8–1.6, 1.3–1.7, 2.4–3.3, 0.8, 3.1–3.7, 0.9 and 0.6–0.9 picocuries per kilogram in various food commodities such as bread, milk, potato, vegetables, root vegetables, rice, eggs, fish and fresh meat in the USA and Germany	Spiers (1968)
In the Indian subcontinent, the value of radium-226 was reported as DL (detection limit) to 0.779 in rice of Kerala region. Similarly fruit crop like papaya and leafy vegetables have reported as DL (detection limit) to 5.31 and 3.68–23.7, respectively, in the region of Tamil Nadu	Iyengar (1990)
Strontium-90 is the radioactive isotope of strontium having 52 neutrons and 38 protons. As per one estimate, around 22.8 and 24.6 picocuries per gram have been consumed through various edible products in the UK and Japan	Ellis (1965)
CS-137 is the radioactive isotope of CS form due to nuclear fission of uranium (U) radioactive particles. As per one estimate, 178 picocuries have been consumed daily through various edible products in the UK	
Lithosphere	
Rock and soil: soil radioactivity depends on either direct absorption of radioactive substances in soil or radioactive particles which are derived from disintegration of several rocks	
Granite rock having 24, 1.4 and 1.3 picocuries/gram (pc/gm) of K-40 (^{40}K), thorium-232 and U-238 (the most common and prevalent isotopes on the earth), respectively	Spiers (1968), Harb et al. (2009)
Limestone rock having 9.0, 0.7 and 0.4 picocuries/gram (pc/gm) of K-40 (^{40}K), thorium-232 and U-238 (the most common and prevalent isotopes on the earth), respectively	
Sandstone rock having 2.3, 0.15 and 0.5 picocuries/gram (pc/gm) of K-40 (^{40}K), thorium-232 and U-238 (the most common and prevalent isotopes on the earth), respectively	
U concentration in soil was 0.3–11.7 mg per kilogram	Scher (2010)
The concentration of radium-based Rn in earth crust was reported as 2 pCi per gram. The earth crust having an average U content of 4 ppm	Fertl (1979)
Hydrosphere	
Hydrosphere is represented by different forms of water body as oceans, rivers, mineral water, drinking waters, etc. Radioactive particles in the waterbody are the major concern today for the environmentalist and health departments	
Oceans have various naturally occurring isotopes of radioactive nature along with some remains of dump nuclear waste in war and weapons. It has 0.01, 0.025 and 0.40 picocuries/gram per litre of thorium-232, radium-226 and U-238 (the most common and prevalent isotopes on the earth), respectively. The concentration of radium-based radioactive particle was reported as 0.07 pCi per litre in the ocean	Earl and Snavely (1989)

(continued)

Table 1 (continued)

Environmental components	References
As per one estimate, the concentration of radium-228 was decreased as per the increasing depth, i.e. from 0.01 (Atlantic surface) to 0.002, by increasing the depth by 1 km. However, the concentration value was increased up to 0.025 pCi/L at the bottom	Campbell (1983)
U is the most common and prevalent isotope on the earth, and its natural occurrence ranges from 0.3 to 2.5 μg/L in groundwater of Himachal Pradesh, India	Singh et al. (2001)
U is the most common and prevalent isotope on the earth, and its natural occurrence ranges from 11.7 to 113.7 μg/L in Punjab, India, from groundwater perspective	Singh et al. (1995)
U is the most common and prevalent isotope on the earth, and its natural occurrence ranges from 1.3 to 13.2 μg/L in tap water in West Bengal, India	Bansal et al. (1988)
U is the most common and prevalent isotope on the earth, and its natural occurrence ranges from 0.03 to 7.8 μg/L in river water of Maharashtra, India	Rao and Shah (1976)
U is the most common and prevalent isotope on the earth, and its natural occurrence ranges from 0.03 to 0.1 μg/L in drinking water of the USA	Fisenne and Welford (1986)
U is the most common and prevalent isotope on the earth, and its natural occurrence ranges from 0.2 to 17.6 μg/L in drinking water of Turkey	Kumru (1995)
U is the most common and prevalent isotope on the earth, and its natural occurrence ranges from 2.2 to 24.0 μg/L in drinking water of Germany	UNSCEAR (2000)
U is the most common and prevalent isotope on the earth, and its natural occurrence ranges from 1.0 to 10.9 μg/L in drinking water of Iran	Alirezazadeh and Garshasbi (2003)
Atmosphere	
Globally, nuclear testing released 117×10^8, 675×10^8, 759×10^8, 0.142×10^8, 0.622×10^8 and 148×10^8 becquerel of strontium-89, iodine-131, barium-140, plutonium-241, strontium-90 and zirconium-95, respectively, in the atmosphere	UNSCEAR (2000)

radioecological impact can be studied through annual monitoring, and even after 10 years, waste is generated from the nuclear station.

3 Different Radionuclides and Their Role in the Environment

Rn are indigenously present in the natural environment as naturally occurring radioactive substance. However with technological progress and anthropogenic awareness, a significant level of interest within the global scientific community regarding the mobility of Rn in the environment has been created (Valles et al. 2009). One such example includes the Fukushima incident which occurred on 11 March 2011. This is a revolutionary incidence in the field of radioecology for the assessment of the mobilization of Rn in diverse ecological systems globally (Al-Masri et al. 2003). As per the report, a huge amount of disintegration products were found around the Fukushima NPP after a month (Ikaheimonen et al. 2009). Rn from anthropogenic source are mobilized through the atmosphere and hydrosphere due to this incident.

Therefore, an urgent need was required throughout the nation to assess the dispersion rate, contamination levels and associated health and environmental problems. This incident necessitated the importance of preparing guidelines that need to be designed for effective management of radioecological events for safety and survilience of human civilization.

Wernsperger and Schlosser (2004) reported Rn of artificial origin such as CS-137 isotopes acts as an ecological indicator for aquatic ecosystem. Variable sources are available for CS to origin. Among them the largest source includes the testing of nuclear weapons in 1950. As per the research reports, the Fukushima and Chernobyl incident has contributed significantly towards CS occurrence in the atmosphere. The Directorate of Radiological Protection and Human Health (2011) reported that during the processing of NPP waste, it was observed that reprocessed waste materials may also be a significant source of contamination. During reprocessing of NPP waste in the form of spent fuel, Europe is leading the front. Developed countries like the USA are yet to begin their reprocessing campaign (Al-Masri et al. 2003). However, this is not the only mode of contamination. It has been reported that scientific laboratories and medical facilities also tend to contaminate the environment by producing hazardous waste (Pienkowski et al. 1987).

Equipments in the industrial sectors consisting of CS radioisotope may spread contamination in a variety of ways (Leon et al. 2011). It includes item lost or stolen, or those who handle these materials may get easily contaminated. These materials are usually considered as scrap parts and therefore sold for recycling purposes, and this is also another route of contamination. Again if these scrapped materials are mobilized towards steel mill for further processing, they may also spread impurity to a significant level. Scrap materials can also find their way to sanitary landfill or sold for recycling purpose and therefore act as a potential threat as hazardous waste (Lozano et al. 2011). Radioactive fallouts from the atmosphere get deposited over the land surface leading towards adsorption over the marine sediment causing further mobilization (Dlugosz-Lisiecka and Bem 2012; Grabowski et al. 2010; Manolopoulou et al. 2011; Meena and Meena 2017; Banerjee et al. 2018).

Radioactive emission originating from radioisotopes varies as per their disintegration rate. For example, a radioisotope having a half-life of up to 30 years emits beta particles which have a higher energy level, and on the other hand, a radioisotope with a shorter half-life may emit gamma rays. The chemical nature of a substance regulates the mobilization of a radioactive element in the environment and ecosystem (Chino et al. 2011). Radioisotopes such as CS-137 have higher water solubility and actively participate in the biological processes of organism such as plant uptake and assimilation due to their chemical similarity with nutrient element K (Yasunari et al. 2011). A higher level of contamination of CS in relation to human being and other biota mainly depends upon the strong attraction of CS towards clay minerals of soils (Marovic et al. 2010). Ionizing radiation such as gamma rays may pose significant radiation exposure for living organism (Franic and Petrinec 2006; Marovic et al. 2010). Another route of contamination includes inhalation of finely suspended materials of CS-137 isotope which may get entry to the human body and other living organisms. Such materials usually generate through wind and water erosion (Franic and Petrinec 2006).

Numerous factors are responsible for the distribution of CS-137 isotope in the environment. The factors include the source, the intensity of emission, the substrate medium and the wind and water flow that are taking place through the medium (Porcelli et al. 2001). Radioisotope deposition in the form of aerosols depends upon the precipitation pattern of a particular area (Franic and Bauman 1993). Such mechanism has been proved by the Fukushima incident where the highest contamination took place in the proximity areas of reactor or areas through which the radioactive plume spread through intense rainfall and wind (Kumblad et al. 2006).

CS radioisotope deposition in the aquatic environment is regulated by the architecture of the ecosystem such as the velocity of water, prevailing dilution mechanism as well as amount of sediments present in the particular site (Takemura et al. 2011). It has been scientifically proven that CS-137 particle can travel a wider distance such as more than 100 of kilometres with a higher velocity of stream flow (Visible Information Center 2011).

For radioactive contamination, irrigation water shows a considerable level of influence. A stream contaminated with radioactive isotope is therefore very hazardous to water and land. It has been found that water withdrawn from streams contaminated with radioactive isotope poses a significant threat in the form of mobilizing radioactivity into the soil environment. Similarly runoff can also perform in a similar fashion to contaminate both water and soil ecosystem (Deutscher Wetterdienst 2011). In this connection, CS-137 radioisotope is a major concern worldwide (Rushton 2003).

The mobilization or route of CS-137 contamination needs to be explored properly in order to develop defensive mechanism to combat such contamination in the agricultural sector as well as effective utilization of phytoremediation technology to inhibit migration of CS-137 from aquatic system to human beings. Such mode of contamination has raised the question of safety of nuclear power generation process. This is actually the backbone of radioecology to proliferate as a new emerging discipline. It is such a subject which deals with the interaction of Rn with nature, processes and methods behind the contamination of radioactivity in the food chain in an ecosystem with reference to the USA. The Chernobyl and Fukushima incident has raised awareness globally across various countries to focus on radioecology as a future threat for human civilization. Due to simplicity in the structural configuration of the radioactive isotope CS-137, it is the most favourable candidate to be used as an experimental aliquot in the radioecological study. On the basis of the chemical nature of CS, which happens to be an alkali metal, more than 20 isotopes of radium are available for exploration (Filipovic-Vincekovic et al. 1991). In recent years more focus on nuclear energy has lead towards CS release in the environment on a macroscale.

The application of Rn in the medical treatment sector has been widely practised (Wang et al. 2018). For treatment of cancer, the use of radioisotopes and radiation therapy is the most common practice (Table 2).

Table 2 Application of Rn for medical purposes

Types of Rn	Characteristics	Half-life for decay	Medical uses	References
Phosphorus-32	Isotopes of phosphorus and its nucleus having a proton and neutron number of 15 and 17. Very less quantity exist on our mother earth	Having short half-life of 14.26 days	Utilize for therapeutic and diagnosis in medical purpose. Used for treating ovarian cancer, blood cancer (erythraemia), etc.	Cheng et al. (2015)
Iodine-131	Isotopes of element iodine and its nucleus having a proton and neutron number of 53 and 78. Major fission products of U and plutonium contributed in the event of Chernobyl and Fukushima nuclear disaster	Having short half-life (8 days) for decay	Diagnosis and treatment of thyroid cancer and used in nuclear medicine	Goldsmith (2017)
Samarium-153	Radioisotope of samarium element and also known as samarium lexidronam, samarium-153 EDTMP and Quadramet as a trade name. It is generally chelated complex	Having very short half-life (46.5 h) for decay	Diagnosis and treatment of breast cancer and lung cancer and used for relief from bone metastasis	Gallicchio et al. (2014), Parlak et al. (2016), Sartor (2004), Yeong et al. (2014)
Radium-223 (Ra-223)	Isotopes of radium and its nucleus having a proton and neutron number of 88 and 135. Very common and discovered by famous renowned scientist Dr Curies	Having a half-life span of 11.4 days for decay	Utilize for therapeutic and diagnosis in medical purpose. Treatment of bone metastases	Gupta et al. (2017), Cox et al. (2015)
Yttrium-90 (90-Y)	Isotopes of radium and its nucleus having a proton and neutron number of 39 and 51	Having very short half-life (64.1 h) for decay	Radiation therapy was done in the medical sector for treating liver cancer and other disorders	Lee et al. (2016), Wang et al. (2018)
Lutetium-177	Isotopes of lutetium having more stable naturally occurring Rn	6.73 days of half-life	Treatment of cancer and others disorders in the body like synovitis	Dash et al. (2015), Bhardwaj et al. (2017)

4 Radioactivity in the Atmosphere

Freshly generated Rn through radioactive disintegration leads to chemical reaction between Rn and trace gases in the air forming clusters. Further it may adsorb over the aerosol surface of the atmosphere leading to the formation of radioactive aerosols. Such type of mechanism is usually influenced by humidity and concentration of trace gases in the air (Porstendorfer and Mercer 1979). The removal of radioactivity from the atmosphere usually takes place in the form of dry and wet deposition. It has been observed that walls and furnitures are the active site of deposition within a building for Rn. Wet deposition is accompanied by various physical processes (Chamberlin 1955). Radioisotopes of radon in the form of two isotopes (radium-220 and radium-222) are directly released from the soil towards the atmosphere. This process is governed by the turbulence of air mass present in the lower atmosphere, i.e. troposphere. Insignificant variation was recorded in terms of radon content among day and night time (Jacobi and Andre 1963).

5 Radioactivity in Different Ecosystems

5.1 Radioecology in the Marine Environment

It involves the studies of radioactivity levels in the coastal side and in the open ocean. It involves technical expertise towards quantification of radiation pollution under the sea ecosystem. Radioisotope K-40 presence in the sea has led to a higher level of radioactivity (up to 13,000 becquerel/m). CS-137 in the form of artificial radioactivity was added into the ocean ecosystem. Nuclear weapon testing in the atmosphere is one of the major factors for ocean contamination through nuclear fallout. For example, in Great Britain (situated at the Irish Sea and La Hague, France), it was observed that the release of nuclear waste material from Sellafield fuel reprocessing plant caused a significant impact. Realizing the gravity of the situation, the level of such discharges has been reduced considerably within the decade.

5.2 Radionuclide Mobilization in the Ocean Ecosystem

Water currents tend to play a significant role for efficient distribution of Rn in the oceanic environment. The main mechanism behind this is that Rn particles adhere to the surface of suspended particles within the water and gradually settle down in the ocean bottom after a certain time interval. By this process the level of Rn in the sediment component is 100 to 10 million times higher in comparison to the level in sea water. Marine biota here plays a significant role within such process. Marine organisms having filtering capacity tend to accumulate Rn by concentration factor of 5–100,000 in comparison to sea water. Different groups of molluscs are used as bioindicator species. Rn released into the aquatic system acts as an effective tool to provide important information related to the migration of Rn in the aquatic ecosystem. For example, in the case of the English Channel, tracing the level of tritium revealed 110–152 days' time period for its transport from a long distance (from La Hague, France, towards the Strait of Dover).

5.3 Inland Water Radioecology

Under such systems it has been found that inland freshwater bodies receiving radioactive waste from varied sources form different types of ecosystems. A similar mechanism of mobilization of Rn in inland system was found as in the case of ocean. Both processes vary between marine ecosystem and freshwater ecosystem as a bioconcentration factor. Under inland system heavy metal presence alters the rate of Rn fixation. Species such as the Asian clam (*Corbicula fluminea*) and the zebra mussel (*Dreissena polymorpha*) were selected as bioindicators due to their ready availability. Radioactivity within living organisms develops due to the balance within decontamination and contamination process which is governed by the uptake and removal process and radioactive mode of decay along with biological degradation.

Radioecology of Terrestrial Ecosystem

The nature of terrestrial environment is highly complex. It is influenced by different environmental setups and topographical features along with different vegetation types and their interactive process such as food chains. Land ecosystem is contaminated through atmospheric deposition. The Chernobyl disaster spread radioactively contaminated air masses for long distances. Radioactive deposition takes place as per the wind motion which mostly takes place during the monsoonal period in the presence of undulating highland.

6 Field Studies of Radioecology

Rn hazard often imposes strong economic impact in the global economy since it involves reclamation and restoration through decommissioning process of the reactors and subsequent cleanup scenario in the affected areas (Samet and Seo 2016). It is astonishing that with such an important aspect, Rn and its ecological consequences are yet to be explored properly, scientifically and economically. There is a big knowledge gap in terms of scientific exploration of radioecology as the regulatory bodies of nuclear energy sources refer that the impact of radioactive contaminants has no such significant impacts. It has also been assumed that wildlife exist in the exclusion zones due to lesser hunting approaches with the purview of being contaminated.

The most significant concern is that with the rising energy demand throughout the world, everyone is shifting from conventional to nonconventional form of energy. In this condition, nuclear energy is a new emerging branch. As per the records till date, 438 nuclear reactors are actively producing nuclear energy, and therefore, they are becoming the significant source for fulfilling future energy needs. The nuclear energy sector is gradually growing day by day with 65 new plants under construction, more than 165 under planning and more than 300 nuclear reactors in the proposal stage. The main problem is that each of the nuclear reactors produces a huge amount of radioactive load from per-day operations. For example, in the case of the USA, boiling water reactors emit up to 100,000 giga-becquerels of radioactive novel gas per annum in comparison to normal pressurized water reactors (Burris et al. 2012).

The Rn of concern includes I-131, CS-137 and Sr-90 generated from day-to-day operations from NPP. In terms of ecological impact, humans are affected in the form of childhood leukaemia (Fairlie 2014), and for nonhuman biota, the impact is solely reflected as heat stress. The consequences of NPP in future would be worse as an unregulated amount of radioactive waste was emitted into the environment. For example, Vermont Yankee NPP situated in the USA was revealed to have more than 2000 sources of leakage of tritium, which is a radioisotope of hydrogen, and was associated with cooling pipes with faulty structure. As it came into the limelight, the power plant was shut down. But there are numerous other power plants in the USA which do pose some sort of radioactive leakage. The ecological consequences of tritium are yet to be explored properly (US GAO 2011).

In the year 1997, the Environmental and Health Ministry created a cluster for radioecological studies at Nord-Cotentin. During their study they prepared an inventory of nuclear waste emitted from NPP. Simultaneously they also assessed the level of exposure to radioactivity by human population and associated risk (Fig. 1) for occurrence of blood cancer. The group was strengthened by the presence of experts from various fields and foreign institutes. The entire work was based on separate models. In the first approach, databases regarding various forms of waste and their migration to human population were studied. The second approach comprises of validity testing of the impact models for radioactivity on human populations including the level of radioactivity in various environmental components. From the study an estimation of possible risk of radioactivity towards the environment and on living organisms was done.

Migration of radioactivity in the air environment is a very critical issue as it was revealed from the Chernobyl disaster. Research studies revealed that aerial contamination of radioactivity under the aegis of air masses migrated from the site of origin to French Alps where the natural mechanism of snowfall made the snow cover of the region contaminated at high altitudinal level in Southern Alps (Mercantour mountains). The entire study produced a hazard map for soil radioactivity. In Isola and Lombarde pass region, an in-depth study of radioactivity level was done. The results reveal variation in the level of CS-137 which depends upon the nature of the soil. The average concentration of radioactivity appeared to be 10,000 becquerel/m^2 which was prevalent in grassland ecosystem and larch (*Larix* spp.) forests under the plantation of spring fern. This study further confirms the migration of CS-137 which depends upon the lithology and topographical features of the region. This study could be helpful in future to assess the level of radioactivity in the upland region

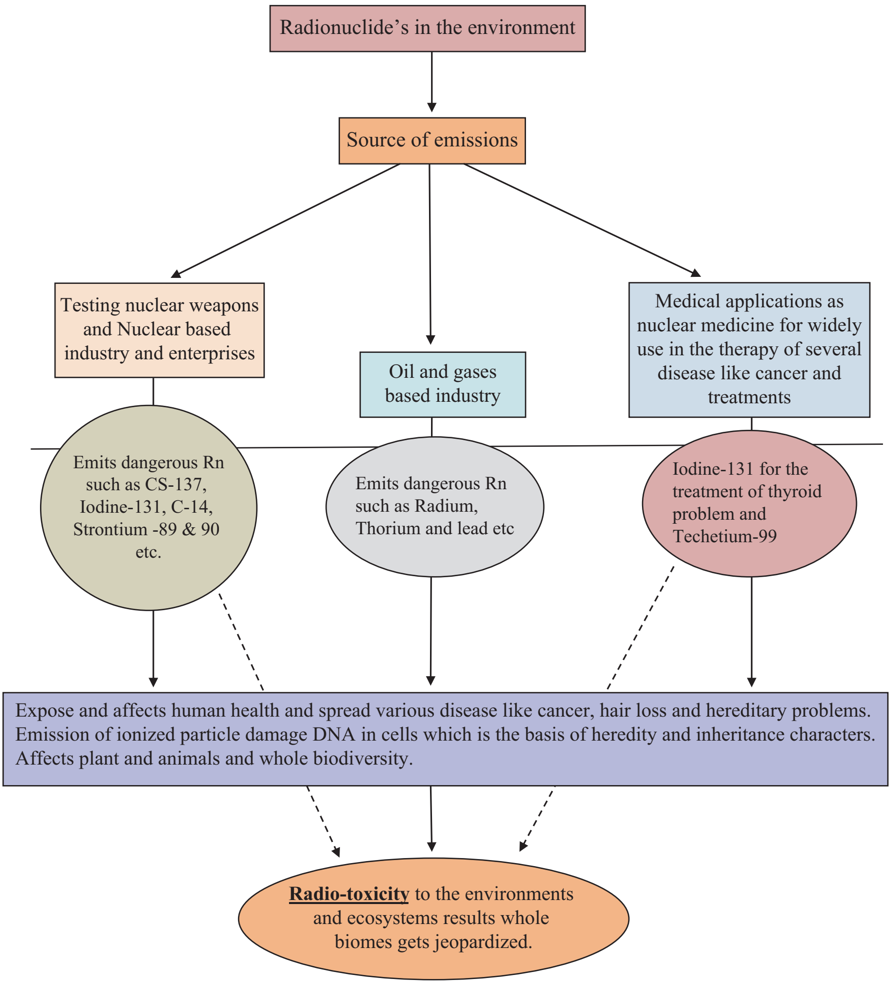

Fig. 1 Radioactive substances and health hazards. (Gilbert et al. 2013; Harb et al. 2009)

where one can locate the problematic area due to higher concentration of CS-137 emitted from the Chernobyl disaster incidence.

Before initiation of NPP in an area, the background concentration of Rn in different components of the ecosystem along with the biota was determined within a range of approximately 40 km surrounding site of establishment which is designated as null point in radioecology as a particular location point. History suggests that Rn are the integral part of earth since its origin. It has been observed that earth is being continuously heated through the disintegration of Rn which has a slow disintegration rate. To effectively explore radioecology, one needs to know about the natural and artificial radioactivity and the mobilization and fate of Rn in the environment. This is a very effective study as it provides valuable information regarding health risks of radioactivity. Technological progress in the form of industrialization, urbanization and mining has promoted much more exposure risk for human beings.

Interrelationship within the species in an ecosystem develops biocenosis which depends upon the variable environmental conditions under which it was framed. It has been found that biota through their ecosystem functioning helps to channelize the naturally occurring Rn in various components of the environment having the least impact on background radiations. Humans are the key for altering the radioactivity through their technological interventions. For example, day-to-day household activities, industrialization and urbanization have led to the redistribution of naturally occurring radioisotopes. Subsequently human also produces artificial radioactivity through synthesizing radioisotopes which have got no previous existence in the environment. Natural radioactivity varies on area basis as well as even on smaller areas. Humans residing over a place without background radiation may get affected if radioactive source emerges in an area. During emergency prepared plan for combating a radioactive disaster, one needs to know about the background concentration of Rn on which the future plan of action would be designed. Monitoring of radioactivity level was undertaken at all times to assess the risk of crossing the normal level of radioactivity and subsequently to assess the impact of natural radioactivity on human health. Scientific research reports reveal that maximum human exposure takes place through ^{220}Ra and its further disintegration.

Research explorations were initiated in order to assess the ecological consequences of natural ecosystems under radioactive threat. In this roadway Mousseau and Moller in the year 2000 initiated the study of likely consequences of Chernobyl incident over avifaunal population of the concerned region. Further in Fukushima the investigation results expanded the scope of the study in the form of observing threats in different organisms such as vegetation, insect community as well as spiders. These studies on Chernobyl and Fukushima mainly addressed the genetic problems in different organisms due to ionizing radiation. Simultaneously it was also aimed to study the adaptive features of organisms in response to radiation exposures.

From the results of such scientific explorations, mutations were found to be the most possible consequences that adversely affected the biota over the area. Not only that the mutational changes were also passed from one generation to another as heritable characters (Moller and Mousseau 2015; Sihag et al. 2015). Interesting findings through the study revealed that the radiation effect was variable in nature among different taxa and plants. It was observed that plants are much more susceptible towards radioecological effects than animals. Mousseau and Moller (2014) reported a case from Joji Otaki that a place situated in Japan revealed higher mutation rates in the existing butterfly communities over the area. Their findings were further cross-checked both under in vivo and in vitro conditions which simultaneously alter the phenotypic structure (Mousseau and Moller 2014). Further progress in the study by Otaki's group, Japan, revealed decreasing level of radioactive effect due to lesser exposure after a span of time interval. Rn of natural origin like U and thorium level governs background radiation level of an area. Some of the areas under high background radiation include Brazil, India, Iran, etc. Moller and Mousseau (2013) simultaneously reported the impact of background radiations mostly affects the immunological response, mutation and expression of new diseases among various biota.

As observed from the past experiences, whitish scar marks appear on the body of birds and also on the surface of the domesticated mammals such as cattle. Partial albinisms in the form of discolouration of the body were observed in the barn swallows along with other avifaunal species (Mousseau and Moller 2014). Such findings can be effectively utilized as biomarkers for radioactive effects of Rn on biota. Studies on germline mutation rates were done for bird species affected by the Chernobyl incident. Comparison with areas without radioactivity revealed abnormal sperm count in barn swallow bird (*Hirundo rustica*) was higher in the affected area (Mousseau and Moller 2014).

Research results suggest that the antioxidant level in different organs and bloods of the birds regulates the radioactive impact over DNA (deoxyribonucleic acid) through Rn exposure. The problem of sperm abnormalities was also found to be higher in the avifauna residing near Chernobyl than birds in other areas with the least Rn concentration. This therefore suggests Rn exposure often leads to sperm abnormality. From a molecular mechanism point of view, it was found the mortality of sperm of barn swallow bird is significantly affected by radiation exposure. Simultaneously antioxidants often play a significant role in sperm generation in relation to reduction of the impact of Rn exposure (Mousseau and Moller 2014). In the case of plants, the impact of radiation as reported by the Chernobyl incident reflects negative impacts of radiation on the viability of pollens (Moller et al. 2016) which ultimately leads to reduced germination rates (Moller and Mousseau 2017). Under radiation exposure, somatic tissue cells reflect abnormality in the form of forming tumours with high background concentration. This may be due to induced mutation rate within the somatic cells.

Radioecological impact in terms of impact on reproductive system is also reflected through lower fecundity rate of the females which leads to lesser egg production. This may lead to higher impact on population growth. For example, various invertebrate species such as insect population size were reported to be reduced in case of Chernobyl incident even after the passing of two decades. However the results of radioecological impact were contradictory in the case of the Fukushima incident because the populations of spiders increased after the incident (Mousseau and Moller 2014). However, this increase may be attributed towards lack of predation of spider (Araneae spp.) population by birds. The sensitivity of mitochondrial DNA at the molecular level becomes high through mutation under exposure to Rn. This was reflected in the case of the Chernobyl incident where DNA base substitution took place for more than 30 bird species. Such events of base substitution tended to decrease the population growth of bird species. Overall both the incidences proved that various biota are incapable of adapting towards ionizing radiation emitted from Rn leading to base substitution. As per recent studies, various game animals reflected higher population strength existing under the exclusion zone of Chernobyl (Lehmann et al. 2016). As per the research reports, some of the biota can show adaptive behaviour towards high radiation (Jonsson et al. 2008). In this context lesser studies have been mediated to assess the adaptive response of organisms towards background radiation which is prevalent in nature (Ruiz-Gonzalez et al. 2016). Further study needs to be designed to assess such adaptive responses towards background radiation level in order to understand the adaptability of organisms living under various radioactive zones in the world (Mousseau and Moller 2014).

CS deposition in the aquatic ecosystem depends upon the particle size and mineralogical composition of soil particles (Qin et al. 2012; Endo et al. 2012). The entry of impurities takes place as runoff from watershed area (Hirose et al. 2008). As per the research reports, CS bioaccumulates in the biota such as benthic organisms, fishes and hydrophytes (International Atomic Energy Association 2001). The Japanese Ministry of Education, Culture, Sports, Science and Technology (2011) reported that humans get contaminated through consuming polluted water and polluted water use for farming or in the form of contaminated plant or fish as food items. The Japan Ministry of Land, Infrastructure, Transport and Tourism (2011) reported that radioactive contamination from watershed may find their way into the drinking water source which is a potential threat for human civilization.

Globally the spread of radioactive contamination takes place through radioactive fallout from the atmosphere and release of radioactive emission from NPP and through major nuclear accidents (Bossew et al. 2007). In the case of the Chernobyl disaster, the spread of radioactivity took place due to unregulated splitting reaction at the nuclear reactor leading to fire disaster (Jasiulionis et al. 2006). As a consequence of that, the wind flow over that region helped to spread the contamination of about 85 pico-becquerels of CS-137 isotope in the form of gas and suspended dust particles (Jasiulionis and Rozkov 2007). In the case of the Fukushima incident, natural events such as earthquake tremor followed by tsunami promoted the release of Rn. Immediately after emission, it spread over the entire aquatic ecosystem and was considered the world's biggest contamination event of radioactivity from the nuclear sector. The effluent of the Fukushima nuclear plant was also a potential source of radioactivity (Morino et al. 2011). Such event was considered as the largest event of human-made Rn contamination in the marine ecosystem in the history (Stohl et al. 2011).

In order to combat such events, conceptual models and computational framework regarding Rn mobilization and their potential route for human exposure need to be studied. In this connection, for the determination of the background concentration of radioactivity, different models have been formulated. In the modelling approach, one can predict the level of radioactive contamination through the food chain such as in the case of grassland ecosystem. From this approach we can further proceed to calculate the precipitation rate along with mobilization rate into the plant through the root system. Then further the animal consuming the plant material will be exposed to radioactivity through bioaccumulation in the body mass and milk. Humans consuming the milk and meat of the animal may get contaminated at a steady rate (Faw and Shultis 1993). One of the common approaches in the management of nuclear waste is deep-sea burial. As a consequence of that, the marine ecosystem has become a potential threat in terms of contamination to the entire human civilization. Researchers have explored the potential route for mobilization of Rn via the route of ocean water and ice caps.

7 Radon Radioactivity: A Case Study

Radon is an inactive noble gas which exhibits the least chemical reactivity. It exhibits short half-life with zero reactivity towards other elemental species forming a chemical compound. It is a disintegrated product of radium which can mobilize at far distances in the air environment. It can accumulate in the alveoli of the lungs, in cracks or fissures in rocky substratum and also in other components of the environment. The removal of radon from rocky substratum depends upon some abiotic factors such as humidity, minerals and temperature. As a naturally occurring Rn, its existence came in front of human civilization some more than hundred years ago due to mining. However, the maximum exposure towards ^{220}Ra and ^{222}Ra occurs from the background concentration present in the air. Under atmospheric condition, the higher presence of Rn takes place through radioactive disintegration naturally.

It has been reported that disintegration of Rn takes place in rocky substratum and 222 Ra migrates through soil and atmosphere. Migration of 220 Ra in lithosphere depends on lithological structure and meteorological condition. Under atmospheric conditions, Rn may become ionized and can combine with atmospheric aerosols to form complex structures. Rn with short half-life can easily disperse from the soil environment.

Different radioisotopes of radon get access in the upper atmosphere by passing through the atmosphere present over the earth surface. Other sources of radon include sea or underground water as well as natural gas which reflects a smaller contribution. It has been reported that a higher level of radon exists in soil than the atmosphere. The environmental gradient of radon was usually maintained by generation of Rn from the radioactive elements. Atmospheric radon concentration is regulated by the surface activity of Rn along with the dilution process of the atmosphere. Radon in indoor environment happens to occur due to their presence in the building material in the form of soil. The main mobilization mechanism in the environment of radon includes transport of radon from soil mineral grains to pores of the building materials and subsequently from building materials to the outer environment.

8 Human and Radioactive Interactions

From an origin of life perspective, radiation as gamma and cosmic rays played an important role for the origin of life on earth surface. It has been observed that life on earth originated due to radioactive interference by the naturally occurring Rn under anaerobic steamy condition at primitive earth. Every living organism on the earth surface is exposed to a minimum level of radiation which is designated as natural background radiation (Table 3). The physical space occupied by an organism per unit area per unit time is known as its habitat. Within a particular habitat, diverse species coexist and undergo biotic interactions through which the functioning of different biomes takes place. It has been observed that for survivability purposes, the biotic community develops their own interactions with the abiotic environment

Table 3 Health impact of Rn on human

Events	Monitored Rn and radiations	Health impact	References
Gulf War event (between the USA and Iraq)	Depleted U[a] as U-238	Health effects like radioisotopes stimulated blood cancer or congenital defects, skin problem, genetic disorders, cancer, etc.	Albert and Marshall (2005)
Nuclear events at Rocketdyne/ Atomics International	U	Within a span of 44 years (1950–1994), more than 2000 workers were evaluated in terms of radiation dose exposure which revealed 441 deaths and cancer incidence in 134 individuals	Ritz et al. (2000)
Nuclear weapon fabrication and assembly at Los Alamos National Laboratory	Plutonium-238, plutonium-239 and tritium/triton/ hydrogen-3 (radioisotope of hydrogen)	3775 workers were exposed to cancer mortality as lung cancer, brain cancer, Hodgkin disease, etc. were predominant in workers	Wiggs et al. (1994)
Atomic weapons research and development, Mayak, Russia	Plutonium	500 workers were exposed to lung cancer mortality	Gilbert et al. (2013)
Thorium processing plant	Thorium (Th-232)	3039 workers were exposed to lung and pancreatic cancer mortality and respiratory disease	Polednak et al. (1983)
Nuclear disaster at Chernobyl NPP at Ukraine	Iodine-131 and caesium-137	Health issues like thyroid cancers of 30 operators and firemen and other major diseases and health disorders	WHO (2013)
Radiation incident in Mayapuri area at Delhi, India (2010)	Cobalt-60 (synthetic radioactive isotope)	Due to radiation effects, few workers and employees suffered burn injuries and illness	Remesh and Vinod (2010)
Disaster in NPP at Pennsylvania, USA. Also known as Three Mile Island accident	Small release of radioactivity due to failure of equipment workability and workers' fault	No any type of injury	Walker (2004)

[a]Note: The term depleted uranium (DU) represents the residual U of isotope U-235

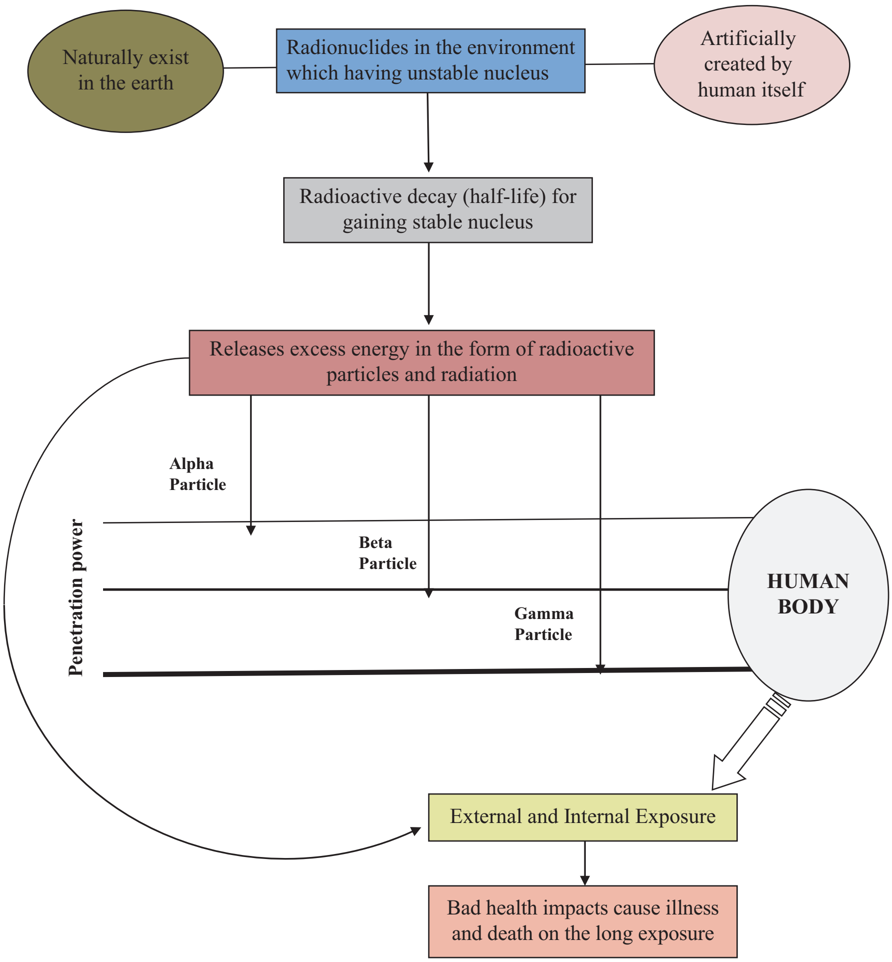

Fig. 2 Human vs. radioactive interactions. (Albert and Marshall 2005; WHO 2013)

(Fig. 2). Under natural conditions, the ecosystem reflects variations at spatial and temporal scale which is dependent upon the interactions between biota and their environment.

From a human perspective, eye cataract is the most common disease due to radiation exposure. Eye cataract was found in the eyes of survivors of the atomic bomb during the end of World War II which simultaneously supports dose-response interactions. It is also reported in the case of bird species expose to high background concentration of radiation. The sign and symptoms include the development of opacity in a single eye or both eyes (Mousseau and Moller 2014). Further scientific reports supported that the case of cataract formation can be used as an effective biomarker to detect radioactive contamination (Lehmann et al. 2016; Datta et al. 2017). However such events may take place due to lack of fitness level in animals.

Radiation may also impose negative impacts on the neurological system in the case of humans. Otake and Schull (1998) reported that survivors of Hiroshima and Nagasaki bombing supported the radiation facts.

As per the results, mentally retarded personality with slow brain development was the most significant impact associated with these events. A similar event was reported in the case of birds and rodents exposed to higher ionizing radiation in the Chernobyl incident (Mousseau and Moller 2014). The singing pattern of birds has also been malformed under radiation exposure. Further in birds, due to higher radiation exposure alteration in the adult sex ratio in the form of more number of males than females, reduction in the population of older birds in comparison to younger birds with higher presence of Rn in the feather of birds. Birds of prey such as goshawk (*Accipiter gentilis Fujiyama*) showed a similar decline in the population trend due to the reduced reproduction rate following the Fukushima incident (Murase et al. 2015). In the case of birds, it was found that peculiar ZW sex determination systems make this group more vulnerable to mutagenic effects (Mousseau and Moller 2014).

Radioactive emissions impose their significant impact in terms of asymmetry, albinism, the size of the brain, cataracts, lesser sperm and tumour formations. A similar level of background radiation does not impose such type of impact. The radioecological impact on the entire ecosystem biota can be categorized as alteration in the physiology, developmental biology, morphology and ethological changes.

9 Ecological Consequences of Radioactivity

In the Arctic region, people are solely dependent upon their traditional life style which is ecosystem based. They depend on food in maintaining their daily livelihood. In this approach all the organisms present in the particular ecosystem are interdependent in terms of environment setup. It would be a unique gesture to know the radioecological impact on such ecosystem setup (IAEA 1992). Radioecological exploration to determine the safety level for human exposure helped to reduce the radioactive exposure to other organisms. The key process that are affected in case of animals include gametogony, that is, gamete formation, and embryogeny, that is, the formation of embryo. These two processes are very much key for both terrestrial and aquatic organisms (IAEA 1992). Animals and plants were found to be much more vulnerable to radiation hazards than human beings.

Under Arctic conditions, the deposition of Rn does not migrate so easily in comparison to other reasons which might be due to lesser mobility under various environmental barriers (Garb 1995). The short span of growth with the moderate presence of different abiotic factors leads to lesser metabolic activity which aids in Rn dispersal (Thomas et al. 1992). In the case of the Arctic ecosystem, it has been found that alteration in salinity levels makes the organisms radiation sensitive. On the other hand, salinity acts as an important factor for regulating the Rn concentration in the cells and tissues of the organisms (Tracey 1995). Therefore, all these abiotic factors make the Arctic fauna more radiation susceptible (IAEA 1988). As per research reports, a radiation dose of 0.2–5 mGy per hour basis found in aquatic organisms reflects increased susceptibility of them in comparison to mammals (IAEA 1988). In the case of population ecology, the inherent natality rate (r) was reduced to zero in the case of *Daphnia pulex* (water flea) under radiation exposure (Krupnik 1993).

Bioindicators for detecting the hazards of background radiation need to be explored for early warnings of radiation exposure. The Organisation for Economic Co-operation and Development in this connection reported that in northeast Atlantic, dump site disposal of nuclear waste materials was done. The study revealed up to 40 years low content of waste material of radioactive origin, nuclear waste of industries and medical sectors along with mismanagement of equipments of NPP for deep-sea burial at northeast Atlantic. In this case the Nuclear Energy Agency continuously monitors its radioecological impact on human and the environment (Nuclear Energy Agency 1985). The study provided fruitful outputs in terms of modelling Rn dispersion, dose rate in past organism and exploration of future dumping site. The study also revealed based on aquatic biota lesser impact on the environment due to projected dumping or deep-sea burial (IAEA 1988).

It is completely a new field to explore, and from the reserve database, it is evident that the ecosystem is highly susceptible towards radioecological impact. As per the study in Chernobyl, the primary productivity level decreased under radiation level which is reflected through slow growth rate of vegetation due to drought stress which may be induced by nuclear radiation hazards (Mousseau et al. 2013). Radiation effect may also include decrease in the decomposition rate of leaf litter at the soil surface under higher exposure of radiation which reflects that the impact directly hampers the microbial community involved in the decomposition process present in the soil (Mousseau et al. 2014). Such impact may have long-term effect in the case of causing alteration in the nutrient turnover rate in the soil and therefore affecting the plant productivity. Such effect can be further correlated with degeneration of soil microbial community under higher intense radiation level which otherwise would have provided sufficient nutrient for the plants to be uptaken for their growth and development.

In terms of ecological interaction, radiation also influences various forms of biotic and abiotic interactions present in the ecosystem. For example, processes such as pollination; productivity of fruits, plant and soil; and microbial interactions are all affected in a negative way (Moller et al. 2012). On a bigger perspective, radiation also influences climate change on a global scale by altering the natural phenomenon such as ecological succession. It is a very severe threat for human population under contaminated area. For instance, reduction in the decomposition rate under the influence of radiation leads to higher presence in relation to soil organic matter which acts in the form of ready source for forest fire, therefore leading to higher intensity of damage in the forested land (Mousseau et al. 2014). As per the reports, leaf litter happens to be highly radioactive, and therefore burning of such type of contaminated material may lead to higher emission and dispersal of Rn in the forms of volatilized Rn (Evangeliou et al. 2015, 2016). In the present context, humans and other living biota are under different forms of severe stresses in the form of biotic and abiotic stress. Radioecological investigations at various levels of environment have proved that biota under radioecological impact are ten times more vulnerable than different stress conditions (Garnier-Laplace et al. 2013; Meena and Yadav 2015).

From a historical perspective, radioecology routes back from 1950 onwards as a consequence of testing of nuclear weapon causing significant damage towards human civilization. The research was aimed towards determination of radioactive level and associated impact upon human being with special reference to agroecosystem. The Chernobyl incident released a huge amount of Rn, and further mobilization took place through wet deposition (Duvernet 1989). Ward et al. (1989) reported that 1 year after the incident, Rn concentration was measured in vegetable and other milk products in Western Europe which is probably through deposition. The mode of contamination changed from aerial transfer to root uptake mechanism as revealed from the natural product from different ecosystems which includes products such as edible fungi, berry and wildlife meat.

Rn cycling was easily studied in the agroecosystem in comparison to grassland and forest ecosystem. Higher variability was recorded in soil and biota of various ecosystems which created problems for measurement of radioactivity in terms of predictive models. The measurement of Rn in natural ecosystem shows significant variation in comparison to agroecosystem as there is predefined accumulation of Rn in different horizons of soil, whereas the agricultural soil is being nurtured and plugged. Therefore the depth of soil horizon is frequently altered in case of soil ecosystem (Frissel et al. 1990). The complex structure of forest ecosystem in terms of species richness as well as biodiversity is lacking for the agricultural system due to monoculture practice (Jhariya et al. 2018a, b; Jhariya and Yadav 2018). Such factors significantly contribute towards alteration in the Rn concentration. Further mycorrhizal infestation in the roots of forest plants often promotes the uptake of Rn through soil-plant system (Monte 1990). With the progress and development of radioecology the interest shifted from aerial transport mobilization towards natural cycling of Rn in the natural ecosystem. Among various Rn studied under radioecology, radiocaesium (RC) is the most studied material due to its existence and persistence in the environment through nuclear fallout, fission and fusion chain reaction.

There is a wide variability of existence of Rn in vegetation as well as in soil. Uneven distribution pattern was recorded for soil without disturbance. Niemann et al. (1989) reported uneven distribution pattern in the soil system of West Germany. The distribution of Rn in soil is governed by deposition rate and retention of radioactivity in soil. The different mechanisms of deposition of Rn include direct precipitation of particle size < 0.01 mm through gravitation settling, radioisotopic aerosols through atmospheric precipitation and dry deposition and dispersal due to atmospheric turbulence (Tikhomirov and Shcheglov 1994).

The deposition of Rn has two modes, i.e. direct deposition and indirect deposition. Direct deposition involves direct transfer from the atmosphere to soil along with resuspension mechanism. Indirect deposition includes mobilization of Rn through vegetation interception, leaf senescence and leaching. The buildup of concentration of Rn takes place in soil due to biotic and abiotic interaction. The overall radioecological deposition on soil surface can be classified into various scales such as at the local level, regional level and national level and overall globally. Precipitation happens to be the key factor in Rn deposition at the local and regional scale. This is evident through their deposition pattern in agriculture soil under monoculture of herbs. Rn level in soil surface is dependent upon various other factors such as canopy structure of the vegetation, topographical feature, edaphic features, biogeochemical cycling in the ecosystem and other ecological processes.

The nature of rainfall and its amount regulate the distribution pattern of Rn. Topography seems to act secondly in the case of the forest ecosystem in relation to the distribution of Rn in forest floor soil. The atmospheric transfer of Rn is also regulated through rain originating from different developmental phases of cloud and performing scavenging activity and further deposition with different rate and efficiency (Apsimon et al. 1992).

Trees act as an effective intercepting agent for Rn in the atmosphere. Various reports are available for trees as intercepting agents of aerosols (Proehl and Hoffman 1994). Tree through its canopy structure accumulates Rn through deposition process. Subsequently they are mobilized into various vegetal parts depending upon the biomass of the plant part. Such mechanism makes them act as effective interceptors. The interception fractions for agroecosystems are up to 0.25 as reported by Proehl and Hoffman (1994) and up to 0.8 for forest ecosystem as reported by Schimmack et al. (1991). Research studies based on field models revealed up to 90% of Rn interception that takes place through the crown cover of trees (Tikhomirov and Shcheglov 1990).

Considering the factor of active surface deposition, one can get higher accumulation of Rn in the case of coniferous plants than deciduous tree species. The phenomenon is the same for shrubs in comparison to annuals (Nelin and Nylen 1994). Leaf morphology also acts as a significant factor for Rn accumulation. According to a study conducted at Europe, different plant species on the basis of their retention capacity were categorized (Fraiture 1992). The nature of forests and climatic conditions governs the rate of deposition of Rn as revealed from the study of Bergman et al. (1991) in the case of the Chernobyl incident. Similarly, Melin and Wallberg (1991) reported 35% dry deposition of Rn in alder (*Alnus* spp.), birch (*Betula* spp.) and beech (*Fagus* spp.) plants. Experimental results further provide an insight upon the fact that the appearance of early leaves in plants may also reflect higher retention of Rn (Feige et al. 1988).

Dense canopy structure also hampers Rn accumulation in the forest floor. This was revealed by a study conducted by Padovani et al. (1990) which reflected a significant level of variation in Rn accumulation between coniferous forest and grassland ecosystem of Italy. The condition was contrary when the plant species were under leafless condition as reported by Guillitte et al. (1990) in Belgium. Such condition causes significant lowering of Rn deposits in the soil of forestland. Under natural condition open forest area can receive up to 100% of wet deposition, whereas densely populated coniferous forest will retain nothing (Fraiture 1992). Within the plant system, the deposition rate varies from the needle to stem to canopy depending upon the vertical gradient of Rn deposition. Variation in the level of interception through forest canopies may be due to larger crown cover both under dry and wet deposition mechanism (Bunzl et al. 1989b).

Under the semiarid condition of Mediterranean forests, the mechanism of dry deposition followed by resuspension coupled with tree canopy retention and interception plays a significant influence on the distribution pattern of Rn from the atmosphere to the plant and soil system. Rauret et al. (1994) similarly reported the mechanism of resuspension for Rn accumulation in the case of Mediterranean forest (Spain) which is evergreen in nature.

The soil deposition in the multistoried forest is a little bit complex mechanism due to higher interception of plants present as ground vegetation. As per the records, the horizontal distribution pattern of Rn depends upon the retention and interception capacity of cryptogamous species. Among the other groups of plant species, lichens and mosses tend to hold higher amount of water making them active sink for Rn. Bryophytes on the other hand are very much prevalent under humid and rainy conditions, and due to their higher biomass, they also show more water retention capacity and could be fruitful as RC sink. Bryophytes have higher potential to accumulate Rn with lesser mobilization to soil component (Giovani et al. 1994). Ecosystem component harbouring bryophyte biomass is problematic for assessing Rn accumulation due to retention of radioisotope.

As per the research reports, forest floor covered by bryophytes tends to have lesser Rn content than forest floor without bryophyte cover (Giovani et al. 1994). For different plant species, water saturation potential is an important parameter for retaining Rn. The more the saturation potential, the more will be the retention power. Ground-level concentration of Rn varies as per the watery content of the canopy. It has been reported that canopies of forest and moss population tend to have higher interception and retention capacity by means of which they accumulate higher amount of RC. Caput et al. (1990) reported about time frame after a nuclear accident which governs the Rn concentration in soil. For example, even 1 year after the Chernobyl disaster, it was found that the vegetation is associated with high dose of radioactive fallouts irrespective of soil characteristics. Further the concentration declined due to transfer mechanism from soil to plant.

Within the natural ecosystem, balance between Rn deposition and depletion acts simultaneously to maintain ecosystem equilibrium. It has been reported that aerosol-bound Rn particle may be removed from the vegetation due to wind action prevailing over the area. On the other hand, resuspension can increase the concentration of contaminants in the concerned environment. For example, the minerals and small particles of soil harbouring Rn can be sent back to the atmosphere through wind flow (Anspaugh et al. 1975), splashing action of raindrops (Mazurak and Mosher 1968) and animal activity (Sumerling 1984). The situation is so critical that even after 3 years of radioactive fallout, the contamination level can be high in the atmosphere through resuspension mechanism (Garland and Pattenden 1990).

Mobilization of Rn takes place through some processes such as interception and wash-off. The foliage cover adsorbs the Rn to a considerable extent. Wash-off is associated in the form of through flow, i.e. droplets of water movement from leaves and stemflow, i.e. movement of droplets of water through stem. Ultimately the adsorbed Rn will reach the soil either by leaching or leaf senescence. The branching pattern of plant species also regulates the distribution of Rn within the plant system. For example, RC in vegetation under temperate condition tends to migrate in the soil along with water which flows along the crown cover downwards.

As a consequence a higher level of radioactivity was reflected near the crown margins than the trunk (Guillitte et al. 1990). In other conditions such as deciduous forest type, centripetal branching was observed. In this case where the situation is just reversed due to stemflow, the Rn concentration is higher in the trunk than the crown, and the minimum value was recorded from crown margins (Schimmack et al. 1991). However the stemflow is regulated by the season. A comparative account shown by Schnock (1967) revealed that a higher level of radioactivity was found under leafy condition than leafless condition. Such differences in stemflow pattern can be a suitable example towards variability in Rn accumulation between temperate and deciduous tree species (Guillitte et al. 1990). Under mixed forest type, the soil concentration tends to be higher due to efficient nutrient cycling capacity of deciduous trees.

Leaching happens to be an important mechanism for mobilization of nutrients within the soil. To this a new dimension was added when Rn migration was found to take place through this mechanism. It is so much important that even in the absence of precipitation, the portion of Rn in the form of washout can leach into the soil on a long-term basis (Ivens et al. 1990). According to research reports, the migration of RC molecule through plant takes place by some sequential phases. Firstly in conifers RC accumulates in the needle part and with subsequent washing gradually gets incorporated in the foliage. After the passage of time, the incorporated CS were released from the needles, and a higher level of CS was accumulated in the canopy (Sombre et al. 1990). While considering the growth of a tree, leaching takes place unevenly among various phases of growth. For example, it has been observed that the maximum leaching takes place before attaining maturity and subsequent death of the leafy material. The span of precipitation is also an important factor for Rn leaching in the soil. It has been found that rainfall of prolonged duration is much more fruitful for Rn mobilization in soil than rainfall of short duration. Quantity also hampers the distribution of Rn.

The rate of litterfall is also a significant factor governing the Rn distribution. It has been found that the litterfall rate is different for different species and accordingly there would be variation in Rn content of various litter layers. Vallejo et al. (1990) reported a higher activity of Rn in *Pinus* needle than younger leaves which are not exposed to radioactive deposition directly. In the case of conifers, RC deposition in the leaves significantly influences ground-level concentration. Guillitte et al. (1990) reported higher level of RC deposition through leaf senescence has undergone absorption of Rn through direct contamination. Further the decomposition process is very slow for *Pinus* needles, and therefore a steady inflow was recorded by them in terms of Rn mobilization (Henrich et al. 1990).

Rn mobilization within soil component takes place through a diverse mechanism. Firstly under mountainous condition, Rn is absorbed in the organic material of soils and is later usually eliminated through runoff. Further removal process takes place as precipitation runoff over the soil surface, as well as through the erosive action which removes the particulate matter (Bonnett 1990). Research reports reveal that under the alpine environment Rn mobilization through runoff leads to higher accumulation at the slop bottom (Maubert et al. 1990). Mobilization of Rn in the form of runoff water is dependent upon the nature of precipitation along with the impermeable nature of the soil surface. Under cold climatic condition, it was observed that Rn deposition was at the maximum for snow-free areas in comparison to areas covered with snow (Gaare 1987). Under such condition the activity of lichen increased due to higher Rn deposition in lichens biomass (Gaare 1987).

Among various biological factors, plant, animals and fungal species are actively engaged in the distribution of Rn in the environment. In the case of fungi, RC is actively accumulated in the mycelium and further concentrated in the fruiting bodies. Fungal hyphae tend to mobilize nutrient in soil and therefore can easily mobilize Rn in different soil horizons (Dighton and Boddy 1989). The mechanism of RC transportation in soil environment takes place through the newly emerged mycelium, through fruiting bodies and through symbiotic plant roots. Fungal biomass has a huge potentially for accumulating Rn on spatial scale which also performs the function of environmental decontamination. Research reports revealed that a higher level of RC was recorded for fruiting bodies than their surrounding soil environments (Seeger and Schweinshaut 1981).

In the case of higher plants, RC accumulation and distribution depend upon the active biomass of the components. Literature review suggests that forest understory stratum is less efficient than upper canopy in terms of Rn retention (Van Voris et al. 1990). In the case of grassland ecosystem, due to their higher growth rate and biomass, they tend to retain a larger amount of RC. In them, most of the part was accumulated in the vegetal part, and the residual content was mobilized into the humus component of the soil. Rn distribution in the different components of the plant system reflects the highest retention in the plant root (up to 20%) followed by tree branches and tree trunks (up to 10%) and the lowest amount (<1.0%) in tree leaves and foliage cover of herbs.

In the case of animals, herbivorous species directly consume the vegetal cover of plants. Therefore, herbivores have been reported to mobilize RC in higher amount than the litterfall of trees. Further such findings were supported by the higher RC content in the meat of herbivorous animals which are fungivores (Pastor and Naiman 1992). Further contaminations spread through defecation process of these animals.

The vertical movement of Rn within the soil system takes place through diverse mechanism which includes chemical interaction between soil and water molecules, colloidal activity of soil, animal-mediated mechanical mixing of soil and release from leakage and litter production by plant and fungal species (Bunzl et al. 1989a). Based upon the different nature of soil, the retention and accumulation of Rn vary according to soil type. To study the mobilization of Rn along a soil profile, retardation factor is one of the keys for this process (Bachhuber et al. 1982).

As per research reports, greater than 15% of RC accumulation has been observed up to 10 cm of soil depth through intra-soil flow mechanism. Such mechanism is associated with intermixing of soil at various soil horizons by the activity of soil mesofauna (Tikhomirov et al. 1990). In the case of the Chernobyl disaster, the initial deposition rate in soil was found to be higher due to heavy showers and intense leaching into the deeper layer of soil horizons (Schimmack et al. 1994). It has been observed that precipitation occurring during radioactive fallout will promote percolation of Rn into deeper soil horizons. Higher persistency of Rn was recorded for organic soil horizon. This leads to immobilization of Rn within the soil organic colloids. Up to a soil depth of 10 cm, Rn gets absorbed from the water flow in the form of leaching (Kliashtorin et al. 1994). Due to organic-rich material in A horizon, it acts as an impeding factor for Rn to migrate downwards.

In the food chain, RC mobilization is regulated by the dual presence of CS and K. Forest litter comprises of three horizons: the litter horizon which initiates the process of decomposition, fermentation horizon which shows the disintegration of litter material and humus layer which contained the decomposed materials in the form of humus (Jhariya 2017; Oraon et al. 2018). Sauras et al. (1994) mentioned about the different important factors for root uptake of Rn into the plant system. Depending upon the humus nature, RC reflects variable distribution vertically. In the organic component of soil, fulvic and humic acids are associated with lignins which regulate the binding of Rn (Andolina and Guillitte 1990). This therefore can be a useful information for assessing Rn concentration in various soil types and its subsequent availability. Variability in vertical mobilization of Rn was reflected in the case of Podzol soils of coniferous forests floor (Rommelt et al. 1990). The reports further also suggest variable nature of migration from organic to the inorganic soil component.

Soil comprising of illite or micaceous mineral component tends to accumulate higher RC. Adsorption to clay minerals usually does not take place due to RC recycling in the organic horizon (Valcke and Cremers 1994). Higher organic matter content in the woodland tends to accumulate more RC than the grassland ecosystem due to higher organic layer with higher retention of Rn. Thiry et al. (1991) reported that top soil containing K and humus content tend to accumulate more RC than mineral layers found in deeper horizons. The span of organic horizon within the forest floor determines the downward migration of RC. However organic matter is not only the factor of CS retention (Thiry and Myttenaere 1993). Soil texture and mineral content often regulate the RC distribution along the soil profile. It has been observed that relative contribution of sand particles and clay in the inorganic part of soil governs the mobilization rate of Rn in soil horizons. RC mobility is influenced through coarse and fined texture of soil particles (Menzel et al. 1987). Soil with high clay content reflects slower migration rate of Rn molecule due to higher adsorption of Rn on the clay surface. Among the silicate clay minerals, lesser sorption potential of Rn was shown by montmorillonite and kaolinite minerals in comparison to higher sorption potential recorded for illite and vermiculite (D'Souza et al. 1980).

Rn concentration in the leaf litter of forest lowers under the influence of moisture level, foliage type and temperature regime of ambient atmosphere. As per research reports, recycling of RC often takes place under wet and dry condition simultaneously in comparison to wet condition all together (Clint et al. 1990). Soil invertebrates such as microarthropods and entrachaeids have been reported to influence the mobilization of RC from soil to litter layer (Bruckmann and Wolters 1994).

The route of uptake of RC varies differently in different plant groups. The situation is more complex for the forest ecosystem. The route of uptake of RC for lichens and bryophytes is the atmospheric deposition. Higher plants tend to uptake RC from soil apart from atmospheric deposition through their root system as well as by the process of mycorrhizal symbiosis.

For saprophytic fungi they tend to accumulate RC from soil and dead organisms. Some parasitic nature organisms including some fungi and higher plants have the capability for RC uptake from living biota. Therefore mosses, lichen and soil fungi can be effectively utilized as ecological indicators in the field of radioecology for their mono-source of uptake of RC. But in the case of higher plants, there are three major components of RC uptake – through foliage, root and mycorrhizal association in relation to total RC content in the plant body.

Bryophytic plants or mosses do not play such active role in the food chain at various trophic levels in the forest ecosystem. However in the case of rainy areas, bryophytes comprise the major total biomass. They appear as thick carpet at the ground layer which therefore facilitate filtration by absorbing most of the atmospheric deposition of RC. This causes lowering of RC concentration in the soil. Research studies reveal the higher trapping ability of mosses regarding wet atmospheric deposition of Rn due to their internal anatomical configurations (Sawidis 1987). Horrill et al. (1990) reported higher level of RC in bryophytes. This can be effectively utilized in radioecology to study bioaccumulation and prepare map for radiation in a particular area (Giovani et al. 1994).

Lichens have the relationship with radioactivity in terms of nuclear fallout from satellite launching (Taylor et al. 1979), radioactivity from the geothermal environment (Matthews 1981) or radioactivity due to mining of U (Petterson et al. 1988). Previous researches on lichen from tundra biome report nuclear weapon testing at concerned biome associated with food chain (Holleman et al. 1980). After the Chernobyl disaster, emphasis was given to study the radioecological impacts on lichens in the temperate system, and lichen was found to be an effective accumulator of RC in comparison to other higher group plants (Hviden and Lillegraven 1961). After the lowering of nuclear weapon testing (1965), it was observed that there was no decrease in the content of RC in lichens (Tuominen and Jaakkola 1973). The RC uptake also varies species wise in the case of lichens as it was recorded highest for terricolous species followed by epilithic species and epiphytic species (Kwapulinski et al. 1985a, b). Atmospheric deposition was found to be very effective in comparison to soil uptake for thallus structure of lichen (Guillitte et al. 1994).

Higher accumulation of CS takes place in the apical portion than basal parts as reported by Hanson and Eberhardt (1971). Higher surface-to-mass ratio facilitates higher RC accumulation by foliose and fruticose species of lichen (Seaward et al. 1988). Globally, before the Chernobyl disaster, higher accumulation of Rn was observed in the case of mushrooms. The report of human concentration doubling was recorded simply because of the higher uptake of mushrooms as food items

(Maushart 1966). Mycorrhizal species and lignicolous species of fungi were reported as efficient accumulators of RC in comparison to saprophytic fungi (Rohleder 1967). After the Chernobyl disaster, higher Rn contents were recorded in the body of deer which primarily fed upon mushroom species (Meyerhof and Marshall 1990). Unequal distribution of Rn in different soil horizons also plays a significant role for the uptake of RC by different fungal species. For example, facultative mycorrhiza tends to depend upon the holorganic region to procure dead organic matter, and on the other hand, obligate species are capable to go inside deeper layers of soil. As a consequence, deeper layers are less contaminated than the holorganic region, and therefore higher accumulation was recorded in the case of facultative mycorrhiza (Guillitte et al. 1994).

In the case of vascular plants, there is species-specific variation in the RC content. However the concentration of Rn varies on the basis of species as well as the nature of soil. Plant foliage is an effective source for food chain contamination of Rn (Muller et al. 1983). Muller et al. (1983) further reported that Rn absorbed on leaves may be translocated through the phloem by growing vegetal part and roots. Leaves with hairy structure are the active site of deposition of Rn. RC under wet condition gets readily adsorbed by the epidermal cells of leaf. Tikhomirov and Shcheglov (1994) provided an insight on Rn mobilization in various forest ecosystem components. Initially trapping aerosol takes place in plant canopy up to 4 years and then subsequent mobilization from the foliage part to leaf litter and then into the soil for ready uptake of roots.

The transfer of Rn from the soil to the plant system is governed by some abiotic factors. Among them soil pH is an important factor. It has been observed that the acidic nature of soil is the most favourable RC accumulation in comparison to alkali soil (Kerpen 1988). Clay content in soil often governs the RC availability for plant uptake. Clay content and CS availability have inverse relationship among themselves. Therefore plants grown under low clay content or in organically rich substratum are highly susceptible towards RC (Cummings et al. 1969). RC emitted from the Chernobyl disaster migrated from the organic layer of the topsoil into the deeper layer of mineral horizons leading to its decline in vegetation. Microorganism residing in the soil rhizosphere zone also actively participates in the RC mobilization from soil to plant system.

Microbial biomass contaminated with RC tends to liberate RC after their death which is readily uptaken by other microbes and plant roots. Different cations exert their influence on the bioavailability of RC in soil. Ions compete for the absorption or adsorption sites in clay minerals and plant roots (Shaw and Bell 1991). The higher presence of K in soils with poor clay content decreases the plant uptake of RC as a consequence of competitive inhibition between CS and K for root uptake (Robinson and Stone 1986). On the other hand, the same potassium in soils with poor cation exchange capacity promotes increase mobilization of RC. Variable results were obtained in this context depending upon the soil texture. Such results indicate that CS readily adsorbs on mineral layer but is fixed biologically in the organic nature of soil. Wauters et al. (1994) reported the role of calcium, magnesium and K towards fixing RC in the presence of micaceous clay structure in soil.

Research reports reveal that climatic alteration has significant influence over RC and strontium uptake by grass species. Mycorrhiza is one of the most potential factors contributing towards Rn cycling under natural and semi-natural ecosystem component. In this connection, for example, ericaceous species exhibit higher rate of RC uptake (Strandberg 1994). The presence of ericoid mycorrhiza under plants of *Ericaceae* promotes higher uptake of RC. The belowground parts of the plant system tend to flourish in organic horizon in which the concentration of RC tends to remain higher making them ready available for plants (Colgan et al. 1990).

In the case of aquatic plants, a higher level of RC concentration has been reported by several workers. Even the RC concentration in *Nymphaea* (water lily) is higher than species of boreal biome which might be attributed towards the higher accumulation of mineral salts to overcome osmotic stress in aquatic system leading to higher concentration of RC (Nelin and Nylen 1994; Varma et al. 2017).

Translocation studies of RC within plant system date back to 1965. The study was mediated through artificial induction of isotope of CS (137) within plant system and other domesticated flora (Hoffmann 1972). Mobilization of RC in different plants and their different parts occurs in variable rates. In beans absorption by the foliage is distributed among other parts of the plant including the root. The translocation of RC from leaves to buds was reported by Middleton (1959). Even in the case of corn, the RC migration was located from leaves to seed (Aarkrog 1975). Wirth et al. (1994) reported the ratio of K to CS is the same in different plant parts indicating the similar distribution pattern of CS as in the case found in K. Considering this fact it can be interpreted that leaves are the main reservoir of RC and could act as a main source for transferring radioactivity from plant to soil system in coniferous forest. In coniferous trees, a higher level of RC has been reported by several workers in the case of needles even after long periods of radioactive exposure. This may be probably due to the migration of RC from the bark of trees to phloem system and then further migration to needles (Block and Pimpl 1990).

Growth dilution is a major influencing factor for the decreasing level of Rn concentration in plants. The growth rate of plants would contribute significantly towards lowering of Rn concentration (Monte et al. 1990). Eriksson (1991) reported the case of growth dilution in barley (*Hordeum vulgare*), peas (*Pisum sativum*) and grass species. He showed that the residence time period of RC was 1 month at the initial phase of growth, and subsequently it reduced at the harvesting period of the crop species due to growth dilution. On time scale basis, direct deposition leads to lowering of Rn level in the grass ecosystem (Eriksson and Rosen 1991).

Dilution phenomena are applicable under the condition of no root uptake. A counterbalance mechanism exists through root uptake in relation to the response of shoot to root migration. Therefore root growth actively participates in regulating the level of radioisotope in plants. Climatic condition significantly influences the distribution pattern of radioisotopes within different plant species. Precipitation and temperature profile were the most significant factors influencing such distribution pattern. Salt and Meyes (1990) reported a significant level of variation in the RC content within June to October. Plants under growing season reflect temporal variation in the radioisotopic concentration as reported by Colgan et al. (1990).

Lembrechts et al. (1990) reported that climatic elements significantly influence the uptake of radioisotope material as well as exposure to radioisotope leading to variation in the level of radioactivity in plants and their further fixing in the soil. The variability in the concentration of CS in the grassland ecosystem in Cumbria is due to climatic variations (Sandalls and Bennett 1992).

Literature is available on Rn accumulation on different plant species. CS were recorded in the basal part of *Luzula sylvatica* (greater wood-rush) species in British pastures during winter season and lesser CS accumulation in senescent leaves than young leaves (Coughtrey et al. 1990). Henrich et al. (1990) reported higher accumulation rate of Rn in older plants than younger plants as affected by the Chernobyl disaster. Mobilization of RC in plants takes place through transfer process between soil and plant. Another research work revealed that under boreal ecosystems decline in the level of Rn in plant species may be attributed towards removal through precipitation, mobilization within plant species and dilution with subsequent growth of plant parts (Bergman et al. 1991). Due to chemical similarity between K and CS, a similar type of variation was observed between the level of K and RC. Most probable mechanism includes basipetal and acropetal mobilization within plant species depending upon various seasons.

In case of pteridophytes, several research works revealed a strong correlation between the temporal pattern of contamination of Rn species and the seasonal development of fungal endomycorrhiza (Bolognini and Nimis 1995).

In radioecology determination of Rn concentration often involves some problems which include some errors in the method of determination. For instance, the plant water is not considered while determining the radioactive contamination in plants on dry weight basis. This error is of least relevance from a radiation protection perspective, but it is erroneous for the studies comparing transfer factors (TF) in different species and studies on translocation of Rn on different plant parts along with studies on seasonal fluctuation. However such errors could be minimized in the case of K by determining the concentration considering both fresh weight and dry weight (Nimis et al. 1988; Meena et al. 2017).

Nimis et al. (1990, 1994) further reported significant variation in the soil features in relation to the rooting depth of different plant species. The level of Rn varies depending upon the species, the age of the material and several other factors. From various experimental results, it was observed that the decline in Rn concentration from young to old leaves is simply due to ageing process which therefore has no correlation with the Rn behaviour in plants.

Modernized approach for assessment of Rn mobilization through plant-soil system includes the TF. For determining mobilization from soil to plant system in the form of TF, ratio-specific activity in Rn within the soil and plant was usually considered. Kuhn et al. (1984) reported the RC activities in soil and grass in northeast Germany for calculating TF values. As per their results TF are the findings of various soil parameters in relation to soil pH (Sheppard and Sheppard 1985). Under natural condition, the TF values reflect sufficient high variation (Boikat et al. 1985). Sheppard and Evenden (1990) reflected that the field results do not usually support the findings of TF in relation to plant uptake. Some major limitations are associated with determination of TF values which considers the total concentration in the soils eliminating the mechanism of bioavailability and speciation, it always considers the steady-state condition but eliminates the dynamicism of the process, and the concentration of Rn in a plant may alter due to their active growth.

The variability of TF values was reflected through the RC concentration in vegetation under the forest ecosystem. Subsequently for proper estimation of Rn concentration in soil, one needs to take care about the Rn concentration in various soil horizons along with the rooting depth of the plant species (Nisbet and Lembrechts 1990). While measuring Rn concentrations in plant, it is better to have a detailed knowledge on the ecology of plant species in relation to screening of factors that is essential for root uptake. The presence of Rn in soil is also a challenging issue as depending upon the soil characteristics, it varies along with soil horizons, and different plant species show different rates of plant uptake of nutrients. Another problem is that organically bound RC acts differently in comparison to free ions that remain present in soil. Both ecto- and endomycorrhiza also influence the nutrient uptake processes of plants.

Under the aquatic system, mobilization of Rn depends upon the level of mixing, turbulence and dilution over time which significantly influences the human exposure. Under such conditions, exposure route through inhalation is a fair chance of occurrence. However, Rn deposited on the sediments of the sea beaches may be transported through airborne spray as was found in some cases (Pochin 1988). The major contributors for human exposure include ingestion. It was assumed that humans consuming food items from the ocean duly contaminated with radioactive substances can be the major path towards human exposure. Within the food chain and food web of the aquatic ecosystem, there exist complex interactions in terms of prey-predator relationship which are very much vulnerable towards radioactive exposure in comparison to human beings. In the case of terrestrial ecosystem, several distinct pathways are available which can be altered through manipulations which are not possible in the case of the marine ecosystem. The reason behind this is that the predatory organisms may feed upon variable preys found in different trophic levels of the food chain as well as they can migrate long distances for sustaining their lives in various ecosystems (Peterson 1983).

Bioaccumulations impose problems for assessing the level of Rn contaminations in the food chain (Fig. 3). It was due to the fact that some mechanism present in nature makes the Rn concentration higher than the background concentration or at releasing point (Peterson 1983). For instance, Rn adsorption over the ocean floor may tend to accumulate on the site at a higher concentration (Eisenbud 1987). Subsequent biological chain reaction is triggered through eating and repeated eating of different organisms at various trophic levels popularly known as biological magnification. To assess biomagnification in organisms, CF (concentration factor) is the key process which indicates the ratio between the concentration of Rn in an organism and the environment. Such studies have been done for different species and different ecological setups.

One needs to take care while assessing the risk of human exposure towards Rn is that the material for which radioactive concentration was measured can be used for

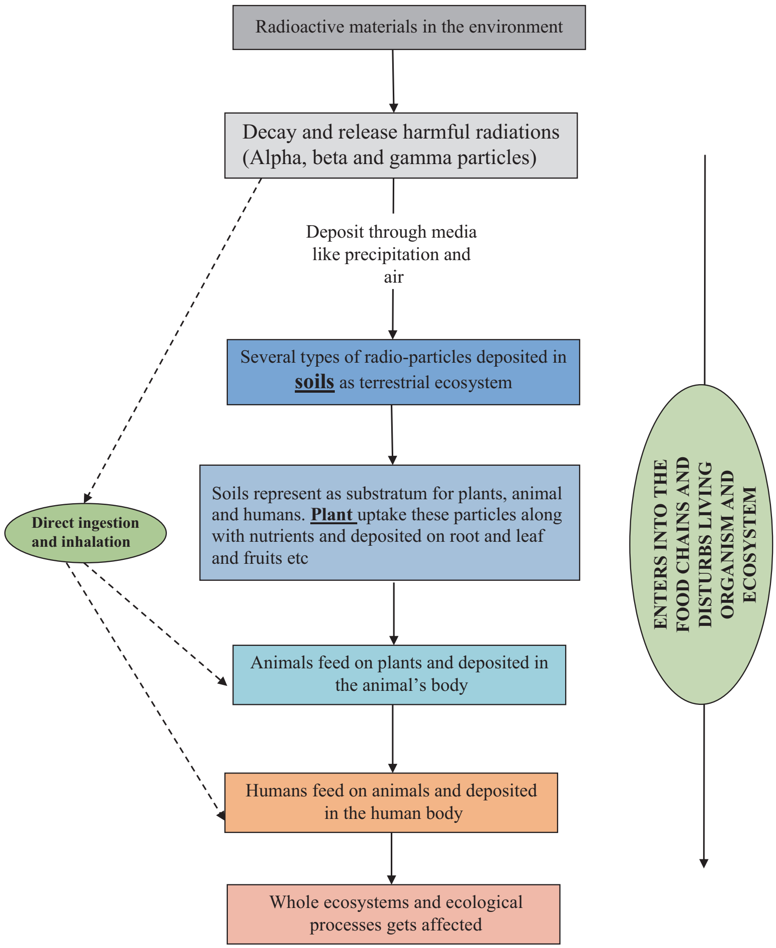

Fig. 3 Radioactive substances in food chain and ecological consequences. (Peterson 1983; Pochin 1988)

human consumption or not. For example, strontium-90 radioisotope is readily adsorbed by the calcareous shell of marine molluscs which is insignificant as human diet (Eisenbud 1987). From the experimental results, it was found that massive accumulation takes place in different organs such as the kidney, liver and other associated parts. Consuming such body parts may pose a potential threat for human beings (Pentreath 1988). This therefore indicates the accumulation of Rn is hazardous in relation to human exposure due to organ specificity. Data should be acquainted regarding CF of specific diet. Seaweeds have been reported to bioaccumulate Rn if grown under the conditions of nuclear waste discharges.

10 Research and Developmental Studies on Radioecological Impacts

Enzymatic reactions proved to be very useful for ecological studies as stable isotopes of Rn reflect significant variation in their natural presence within different components of biological material present in the ecosystem. In the ecological studies, the major aim was focused towards assessment of abundance and depletion of naturally occurring stable isotopes in the environment. In such studies stable isotope ratios were represented as delta notation.

Variation in the natural abundance studies of radioisotopes helps to formulate the trophic nature of food chain of animal communities. The enzymatic fractionation of radioisotopes during nitrogen metabolism leads to 5% increase at successive trophic level. For example, the hair keratin of carnivores was more N enriched than herbivore community reflecting the role of animal protein. Such studies could be effectively utilized for assessing the radioecological impact on human population consuming meat and those who are consuming vegetables. Detection of natural abundance of radioisotopes is required to trace the changing food habit in our ancestors. It also helps to detect the social status of dead individual.

From an ecological standpoint, C (carbon) isotope ratios reflect lesser variation in various trophic levels of food webs but can provide necessary information in relation to the feeding behaviour of organisms. A significant metabolic difference exists between the vegetation under warmer climate and cold climatic condition. Such metabolic differences lead towards differential rate of accumulation of Rn in the herbivore community that feeds upon contaminated food material. The measurement of Rn level helps in a multifaceted way as it can be effectively utilized to measure the concentration at various trophic levels in order to assess the level of contamination. Simultaneously it can also be used by the archaeologists to measure the cultivation of a particular crop species in a prehistoric period (Wagenmakers et al. 1993).

Stable isotope studies have been conducted in the living tissues to determine the pollution load. For example, determination of the level of sulphur in moss species were used to determine the pollutant sources. In radioecology, the concentration of natural Rn has also been used to determine the migratory route of birds (Hobson et al. 2003). Kreuzer-Martin et al. (2003) mentioned that the utilization for determining the site of origin of spores of *Bacillus* species is done through the presence of radioisotopes in the water used in the process of fermentation. In the case of fungi, radioisotope studies are largely being restricted on macrofungi. As per the earlier research reports, different habitats and ecosystem types representing variable vegetation communities tend to accumulate variable rate of Rn concentration (Stapp et al. 1999; Yadav et al. 2017).

Under this condition it is better to monitor the background or ambient concentration of Rn in different components of the ecosystem. Gebauer and Taylor (1999) reported the variable rate of nutrient uptake in different fungal species which reflected the differential rate of nutrient uptake by the respective species. A significant level of variation of radioactive N and C species was observed in different fungal communities inhabiting various woodlands (Kohzu et al. 1999). In such condition greater potentiality of uptake and degradation of radioisotopes (15 C) was reported by ectomycorrhizal fungi in comparison to saprotrophic fungi. Several experimental works have been conducted towards determining the rate of depletion of radioactive C molecules in ectomycorrhizal species which reflected their host specificity (Hogberg et al. 1999). In another study conducted by Hedger (1986), higher number of basidiocarp in conifer plantations was recorded. Chapela et al. (2001) recorded data on radioisotopes, radiocarbon analysis along with basidiocarp studies revealed that *Suillus luteus* (slippery jack fungus) is having a significant contribution towards the depletion of radioisotope of C under conifer plantation.

In order to assess the nutritional biology of a fungal species such as waxcap fungi (*Hygrocybe* spp.), one can go for stable isotope analysis for their growth in nutrient media and susceptibility towards nitrogen fertilizer application. Radioisotope ^{13}CO was used by some workers for the monitoring of nutrient mobilization in the soil ecosystem (Ostle et al. 2000). Radioisotopes of C were also determined under in situ condition with the aid of mobilization of C from plant to microbial community of soil. Further as per another research report, Johnson et al. (2002) reported that a certain amount (6%) of the fixed Rn C in the pulses were released after 21 h through vesicular arbuscular mycorrhiza.

11 Conclusion

During the early phase of radioecology, the main exploration was aimed towards assessing the level of variation in the radioecological data under artificial condition of nuclear accident events in comparison to natural systems. The future of radioecology addresses two different aspects such as ecophysiological aspects on one hand and system ecology on the other. Ecophysiological studies would help the scientific community of the world to investigate the mode of action of radioisotope within the plant system along with their physiological functions within the plant system. Radioecological perspective can be addressed under the studies of various nutrient cycling processes that occur in nature naturally. This could be better achieved through interlinkage between radioecology and vegetation ecology and science.

Further information procurement is required in terms of interlinkage between Rn and the ecosystem. One of the biggest challenges is to assess the mobilization and root of exposure of human beings to Rn. The best effective management includes reduction of sources of Rn emission. Information gap is present regarding the effectiveness of reducing radiation hazards to a considerable extent or not. This requires collection of data both on-site and off-site from various possible sources. Food chain migration should also be properly evaluated and monitored in order to reduce the ecological consequences of Rn contamination. Policy framework for hazard reduction should be oriented towards a taskforce development which would include affected people, and their suggestions should be incorporated in the framework of policy instrument aiming towards sustainability of mankind.

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Effective Role of Microorganism in Waste Management and Environmental Sustainability

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Contents

Abstract

Environmental protection and sustainability is one of the major concerns in present scenario. Continuous release of harmful waste and contaminants due to improper industrialization and unchecked urbanization possesses greatest threat

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to mankind directly in short as well as long term and also puts a tremendous pressure on the natural resources. Unscientific and ill-management of urban and industrial wastes and contaminants has handed over the ecology and environment to the hand of endangered sustainability. So it is the time to make correction and remediate the polluted NR in such a way that brings a sustainable and habitable ecosystem for the future generations. Waste generation has a positive correlation with the economic development which is much observed in the Western countries and also in developing countries like India. Waste generation in India shows different trends, and urbanization plays a significant role in waste generation. In India total solid waste generation is about 42 million tons/year. Hazardous waste treatment requires more effective and green technologies. In this context microorganism plays a promising role. The unique nature of microorganisms can be used effectively for resurrecting the environment. Microorganism can act as magic bullets for bioremediation of contaminated sites and biodegradation purposes. Now a day microorganisms are effectively used together with nanotechnology, termed as nano-bioremediation to clean up radio active wastes. Moreover, the use of genetically modified organisms (GMOs) in combating pollution in extreme polluted condition makes the microorganism a boon to human welfare. This chapter gives an insight into different types of wastes and explains how microorganism can be used effectively for waste management (WM) and sustaining our environment in a greener way.

Keywords

Environment · Industrialization · Microorganism · Sustainability · Urbanization · Waste

Abbreviation

C	Carbon
DDT	Dichlorodiphenyltrichloroethane
GMOs	Genetically modified organisms
HC	Hydrocarbons
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
N	Nitrogen
OC	Organic compounds
OM	Organic matter
PAHs	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyl
PVC	Polyvinyl chloride
TCE	Trichloroethylene
WM	Waste management
WW	Waste water
XC	Xenobiotic compounds

1 Introduction

Rapid urbanization, industrial revolution and tremendous pressure of population on the natural resources put great stress on the global environment. Various unscientific activities of modern civilization generate huge quantity of wastes which lead to pollution (Raj et al. 2018a, b). Moreover increased rate of consumption of raw materials by the large-scale industries results in dumping of huge quantities of chemical contaminants and radioactive wastes in the environment, leads to irreparable damage to the overall biosphere. The generation of waste is the main factor for a loss of materials and energy and raises environmental consequences and cost on society for its collection, treatment, disposal and overall management (Jhariya et al. 2018). Generation of harmful waste in India is directly related to the development of the cities and has a significant variation among the cities. If the rate of industrialization increases it is thought that the amount of wastes will also increase (Sharma and Shah 2005), unless application of scientific waste management.

The scenario of waste management (WM) is significantly different between developed and developing nations because developing nations are lacking of proper collection and disposal mechanism of waste. So, WM has become very critical and receives priority due to progressive concern related to environmental degradation and sustainability (Brewer 2001). Uncontrolled, haphazard and unscientific means of dumping of wastes on the outskirts of towns and periphery of villages results in overflowing landfills, which are not only impossible to return to a suitable condition but also have solemn environmental implications in terms of soil and groundwater pollution and contribution to global warming.

An effective or operative system of WM is the need of the hour and should be economically and environmentally sustainable. There are various popular methods of WM and treatment which are practised regularly such as the following: (1) Incineration method – here wastes and trash materials are treated with high temperature. (2) Sanitary landfills – this method is more useful and practised throughout the world**.** Practically sanitary landfills are the sites where wastes are kept isolated from the environment. (3) Recycling – it means transformation of materials into new form for use. (4) Avoidance and reduction – avoidance means reuse of second-hand products, designing reusable products and, instead of buying new, repairing broken items.

So cleaning of polluted environment in a sustainable way is very much necessary; in this regard the role of microorganism in WM and biodegradation of contaminants has intensified in recent years (Banerjee et al. 2018). Different microorganism based biotechnological tools such as bioremediation, biodegradation, biocomposting and biotransformation have been used to accumulate and degrade huge range of contaminants effectively (Banerjee et al. 2018). Maghraby and Hassan (2018) reported that *Cladophora* sp. (green algae) has high bioaccumulation capability for toxic metals and can be used as potent and alternative WM agent. Moreover, microbial ecology is a major important factor for proper functioning of biological processes of waste water (WW) treatment systems. Martinez et al. (2018) demonstrate that archaea and bacteria are dominant in the bioreactors of

WW treatment system in the polar arctic region in Finland. Nowadays, nanoparticles have been used effectively to enhance the activity of microbes, termed as nanobioremediation. In the USA, *Deinococcus radiodurans* (extremophilic bacteria) is used in radioactive waste removal strategies as it is a radioactive-resistant organism and can withstand radiation naturally (Brim et al. 2000; Varma et al. 2017).

So use of microorganisms with different biotechnologies is the most effective method to treat different wastes, in addition to being eco-friendly, cost-effective and environmentally sustainable method. The main objective of this paper is to propose and promote the application of most affordable and environment-friendly method for treating polluted waste with the use of different microbial agents towards environmental sustainability.

2 What Is Waste?

Waste is generated from human activity mostly**.** Rapid and unplanned development and modification of livelihood all over the world put complexity in the generated waste. Overall biosphere is degraded rapidly due to continuous release of hazardous pollutants from different industries throughout the world. Rapid expension of health-care facilities and modernization of agricultural practices generate large quantity of biomedical and agricultural wastes which brings adverse effect on environmental health. There are three kinds of wastes mainly such as solid waste, liquid waste and gaseous waste.

3 Classification of Waste

Waste can be solid, liquid and gas or waste heat. Waste is classified by its source and by its characteristics. Waste products can be differentiated according to their source and types. Generally there are four sources from where waste can be generated such as industrial, municipal, biomedical and electronic. Waste can be classified on the basis of different criteria such as based on matter, based on degradation feature, based on environmental impact and based on the source. Each category may be of different types which are shown on Fig. 1.

4 What Is Waste Management?

WM is basically the storage, collection and disposal and managing of waste materials. The main aim of WM is to reduce the effects and consequences of wastes on human health and environment. It continues to be a rising challenge with rapid urbanization, industrial revolution and tremendous pressure of population on the NR that put great stress on the global environment. WM has basically four parts – industrial, electronic, municipal and biomedical – and all of these wastes are supervised by particular policies. The concept of 4R theory (refuse, reduce, reuse and

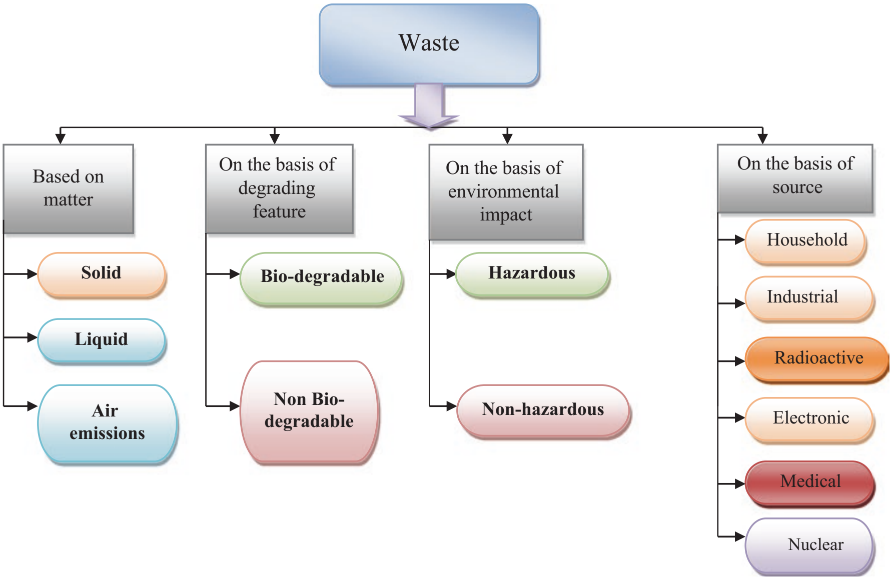

Fig. 1 Different types of waste

recycle) has been applied to the basic principles of WM. In India strategy for WM depends on waste generation, store, collection, transportation, recycle, treatment and disposal. Some of the commonly used WM methods are landfills, incineration, composting and gasification. Schematic view of WM system is shown on Fig. 2.

4.1 Microbes in Waste Management

Microbial biotechnology in WM is the process of utilization of modern scientific tools and techniques which use a wide variety of microorganisms in controlled condition without disturbing the ecosystem. Most common and efficient methods adopted at various level of WM are composting, biodegradation, bioremediation and biotransformation. A wide variety of microorganisms have been used effectively for WM such as *Bacillus* sp., *Corynebacterium* sp., *Staphylococcus* sp., *Streptococcus* sp., *Scenedesmus platydiscus*, *S. quadricauda*, *S. capricornutum*, *Chlorella vulgaris*, etc.

4.1.1 Composting

Composting is an aerobic decomposition process and is facilitated by a diverse population of microorganisms. This process has been widely practised for different types of wastes by means of metabolic activity of microbial consortium. Composting has been used to transform and stabilize organic waste into more safer and stabilized form that can be used in various agricultural practices (Garcıa-Gomez et al. 2005). It is an economically and environmentally appropriate method for handling

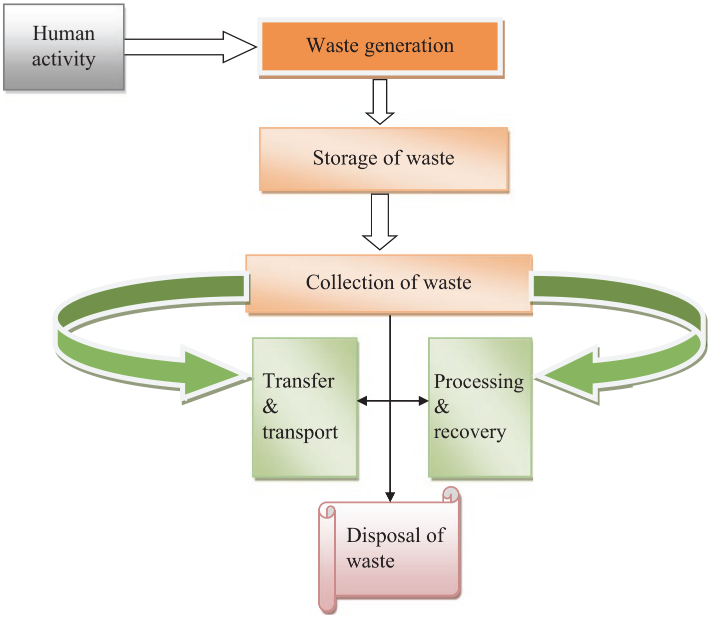

Fig. 2 Schematic view of WM system

waste. The main product of composting is humus and plant nutrients, and carbon dioxide, water and heat are the by-products (Abbasi et al. 2000). Different types of microorganisms such as bacteria, actinomycetes, yeasts and fungi are involved in this process. Composting occurs in three different phases: mesophilic phase, thermophilic phase and cooling and maturation phase. Two factors regulate the duration or length of the composting phases: the types of composting organic matter (OM) and the efficiency or effectiveness of the process ascertain by the degree of aeration and agitation.

Factors Related to Composting

Microorganisms

Several microbes are very much effective to oxidize or decompose different organic compounds (OC) into a more simple and stabilized end products (Atalia et al. 2015). Report suggests that there are certain kinds of microorganisms such as mesophilic bacteria, actinomycetes, fungi and protozoa which colonize a heap of biodegradable solid waste (Gajalakshmi and Abbasi 2008). These microbes can grow in the temperature range between 10 and 45 °C and effectively degrade degradable components (Cooperband 2000; Hellmann et al. 1997). Thermophilic phase is the active phase of composting and can last for several weeks. In the thermophilic phase, most of the OM is degraded (Gajalakshmi and Abbasi 2008; Meena et al. 2018).

Temperature

It has been reported that favourable temperatures for composting to occur is at the range of 52–60 °C (MacGregor et al. 1981). During composting the maximum temperature goes up to 60–70 °C, where most of the microbes are not as much active. Composting process can be paused or significantly steady at the temperature that is below 20 °C. It has also been reported that temperature above 60 °C can reduce the microbial activity, because temperature at that level cross optimum thermophilic borderline of microorganisms (Gajalakshmi and Abbasi 2008).

pH

Composting process is greatly affected and influenced by the pH value. Different composting microorganisms prefer different pH ranges. pH range within 6.0–7.5 is ideal for bacterial development, whereas pH in between 5.5–8.0 is ideal for fungi (Gajalakshmi and Abbasi 2008). If somehow the pH value crosses 7.5, it results in nitrogen (N) loss (Gajalakshmi and Abbasi 2008). pH between 6.5 and 7.5 is probably the favourable temperature for a wide range of microbes (Bharadwaj 1995). It has been reported that bacterial activity is significantly hampered or even inhibited below pH 5.0 (Gajalakshmi and Abbasi 2008).

Moisture Content

To start compost the suitable and ideal moisture content is generally 60–70%. But at the final stages, 50–60% is the optimum moisture content. Moisture content higher than 75% and lower than 30% significantly reduces microbial activities (Bertoldi and Vallini 1983). A proper balance between microbial activity and available oxygen effectively manages the moisture content (Gajalakshmi and Abbasi 2008). Excess moisture creates anaerobic conditions which results in undesirable products and bad odour.

Carbon and Nitrogen Ratio

C and N are both essential for microorganism. C is the principal energy source, and N is important for growth of the microbes. Rapid and entire humification of a substrate basically relies on C/N ratio which is initially in the range of 25 and 35 (Gajalakshmi and Abbasi 2008).

Particle Nature and Size

Nature and the size of particles are very important for composting. Particle size affects oxygen availability into the pile as well as microbial ingress to the substrate. Particles which are smaller in size increase the surface area needed for microbial attack (Atalia et al. 2015; Kumar et al. 2018), and particles which are larger in size minimize the surface area available for microbial attack which leads to slow down or even stop the composting machinery (Zia et al. 2003).

4.1.2 Biodegradation

Biodegradation is a biological way of degradation of chemical compounds (Alexander 1994). In this process living microbial organisms are used to degrade

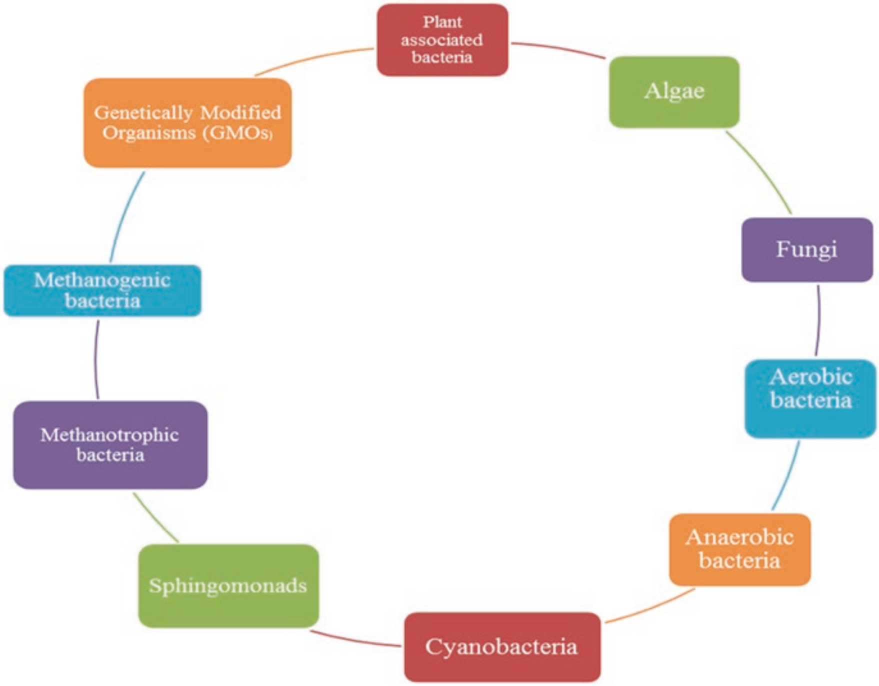

Fig. 3 Different types of microbes involved in biodegradation process

organic substances into smaller compounds (Marinescu et al. 2009). Biodegradation is closely associated with WM and environmental remediation (Marinescu et al. 2009). In terms of microbiology, biodegradation is degradation of OC by a huge diversity of microbial population mainly bacteria, yeast and fungi. Different types of microbes involved in biodegradation process are shown on Fig. 3.

Degradation Capability of Bacteria

Several bacteria have been reported as having hydrocarbon (HC)-degrading ability (Yakimov et al. 2007). This bacterium can biodegrade HC under aerobic and anaerobic conditions, but anaerobic biodegradation is more significant (Wiedemeier et al. 1995). A wide variety of bacteria having HC-degrading ability were extracted from marine environment (Floodgate 1984). Kafilzadeh et al. (2011) isolated different types of bacteria which are good biodegrader of HC; examples are *Bacillus* sp., *Corynebacterium* sp., *Staphylococcus* sp., *Streptococcus* sp., *Shigella* sp., *Alcaligenes* sp., *Acinetobacter* sp., *Escherichia* sp., *Klebsiella* sp. and *Enterobacter* sp. of which *Bacillus* sp. has the best HC-degrading capability. Successful removal of pesticides by the addition of bacteria also has been reported to degrade pesticides from many compounds such as atrazine successfully (Struthers et al. 1998). It has been reported that dichlorodiphenyltrichloroethane (DDT) is degraded by isolates of *Bacillus* sp., *Stenotrophomonas* sp. and *Staphylococcus* sp. from contaminated soil (Kanade et al. 2012).

Degradation by Plant-Associated Bacteria

Bacteria associated with plants such as rhizospheric bacteria and endophytic bacteria are effective biodegrader of toxic compound in contaminated soil (Divya and Deepak Kumar 2011). Plant growth-promoting rhizobacteria are naturally occurring bacteria which are found in the rhizosphere of plant roots and promote growth stimulation in plants (Saharan and Nehra 2011). In most of the cases, the association between plant and bacteria is beneficial for plants as these bacteria help in N fixation and enrich the soil with nutrients (Tank and Saraf 2009; Meena et al. 2015). For example, an important bacterium, *Pseudomonas* spp., has plant growth-promoting rhizobacteria activity and also has the ability to degrade HC (Hontzeas et al. 2004).

Some soil bacteria often promote plant growth, known as plant growth-promoting bacteria. These bacteria are also efficient up-taker of heavy metal from the contaminated soil. Various mechanisms have been applied by this bacterium for metal uptake such as production of organic acid and bio-surfactant and result in reduced toxicity in root and promote plant growth (Wu et al. 2006). Plant growth-promoting bacteria act as a supplement in phytoremediation of metal and can boost plant growth in high metal concentration (Glick 2010).

Microfungi and Mycorrhizal Degradation

Microfungi are aerobic and belong to eukaryotic microorganisms which include unicellular yeasts to mycelial moulds (Rossman 2008). Fungi also have degrading capacities like that of bacteria and OM which are in dissolved state are successfully metabolized by them. Fungi can reproduce and flourish in low moisture content and low pH site which suit them in OM degradation (Spellman 1997). Fungi are considered as the most efficient biodegrader of natural polymeric compounds if they are equipped with extracellular multienzyme complexes. Mycorrhiza is an association between a fungus and roots of a vascular plant. Fungus may be either intracellular or extracellular and play a significant role in soil livelihood.

Different aromatic compounds may be utilized and converted co-metabolically by several yeasts. *Trichosporon cutaneum*, an example of soil yeast, has been reported to have specialized energy-dependent uptake systems for several aromatic compounds (Mörtberg and Neujahr 1985). Alkane-utilizing yeasts such as *Aureobasidium pullulans*, *Rhodotorula aurantiaca*, *Candida lipolytica*, *C. tropicalis* and *C. ernobii* have been reported as an effective diesel degrader (De Cássia et al. 2007). Mucha et al. (2010) reported that *C. methanosorbosa* BP-6 is able to biodegrade aniline. Microfungi are also reported for transformation of different organic pollutants such as biphenyls, polycyclic aromatic hydrocarbons (PAHs) and different pesticides (Fritsche and Hofrichter 2000).

Degradation by Algae

Though algae are also able to biodegrade different kinds of HC, their involvement in HC biodegradation is still not well reported (Das and Chandran 2011). Walker et al. (1975) stated that *Prototheca zopfi* is a good agent for the degradation of different aromatic compounds. Wang and Chen (2006) demonstrate some algae which are capable of up-taking and degrading PAHs. Examples are *Scenedesmus* *platydiscus*, *S. quadricauda*, *S. capricornutum* and *Chlorella vulgaris.* List of microorganism involved in biodegradation process is listed in Table 1.

4.1.3 Biodegradation of Xenobiotic Compounds (XC)

What Are XC?

Xenobiotic (Greek *xenos* = strange, foreign, foreigner) compounds are human-made chemical compounds that are foreign to the nature. They are highly thermodynamically stable, hence are relatively persisting in the environment. The main sources through which XC are released into the environment are chemical and pharmaceutical industries which generate varieties of xenobiotic and synthetic polymers. Modernization of agriculture and mining produces huge quantities of fertilizers and pesticides and releases heavy metals into biogeochemical cycles. Toxic chlorinated compounds released from the pulp and paper industry and accidental oil spillage in large quantity make the situation more catastrophic. The general diagram of probable fate of XC in the environment is provided in Fig. 4.

Impact of XC on Biosphere

Xenobiotic substances are relatively new to the environment, hence not easily removed. XC are toxic and show adverse effect on public health such as disrupting various cellular pathways that are responsible to regulate development and growth. XC can put its adverse effect on lower and higher eukaryotic organisms (Dermatas and Meng 2003; Di Palma et al. 2003; Hrapovic et al. 2005; Huling and Pivetz 2006; Hyman and Dupont 2001; Sihag et al. 2015). The persistent and non-degradative nature of the XC resulted in bioaccumulation or biomagnification and is also able to incorporate into the food chains (Marchiol et al. 2007; Meagher 2000).

Mechanisms Involved in Biodegradation of Xenobiotic

XC is hard to break down and degrade due to its recalcitrant nature. For breaking down such compounds, different microorganisms and their enzymes play a

Table 1 List of microbes involved in biodegradation

Microorganism	Waste compounds	References
Pseudomonas putida	Benzene and xylene	Safiyanu et al. (2015)
Gloeophyllum trabeum, *Trametes versicolor*	Hydrocarbons	Karigar and Rao (2011)
Acinetobacter sp., *Microbacterium* sp.	Aromatic hydrocarbons	Simarro et al. (2013)
Pseudomonas cepacia, *Bacillus cereus*, *Bacillus coagulans*, *Citrobacter koseri*, *Serratia ficaria*	Crude oil	Kehinde and Isaac (2016)
Micrococcus luteus, *Listeria denitrificans*, *Nocardia atlantica*	Textile dyes	Hassan et al. (2013)
Bacillus, *Staphylococcus*	Endosulfan	Mohamed et al. (2011)

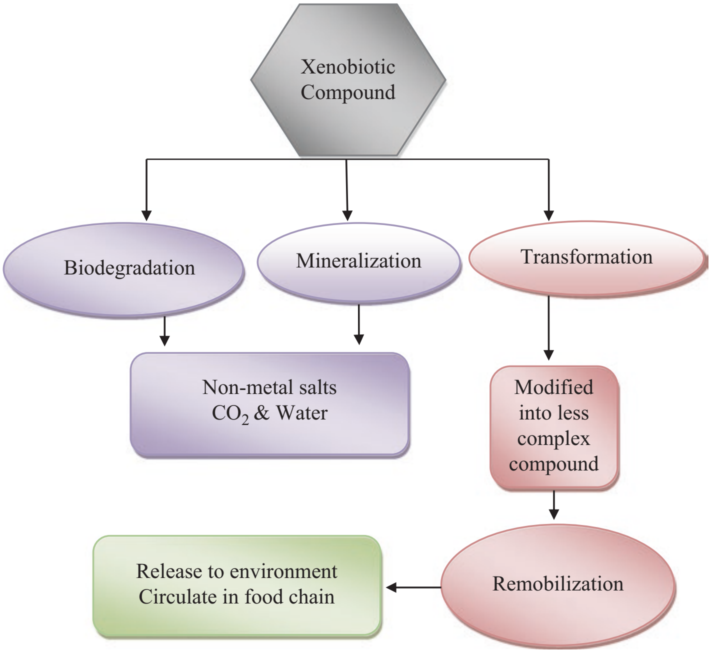

Fig. 4 Probable fate of XC in the environment. (Source: Gren 2012)

significant role. Several studies indicate that in comparison to yeast and fungi, bacteria are the principal microorganisms for xenobiotic detoxification. The role of protozoa and microalgae is very low in xenobiotic degradation. *Pseudomonas* sp. and *Bacillus* sp. are potent and effective in the degradation of xenobiotic among the bacterial group (Janssen et al. 2005; Tropel and Van der Meer 2004).

Among the fungus, *Aspergillus niger*, *Gliocladium deliquescens* and *Penicillium italicum* have the potential to degrade various XC (Ekundayo et al. 2012). Microorganisms degrade different XC aerobically or anaerobically. Petroleum HC, phenol, naphthalene, benzene, toluene etc. are some of the xenobiotic compounds rapidly degraded by the aerobic degradation process, whereas chlorinatedd dioxins and some pesticides like DDT and polychlorinated biphenyl (PCB) are the targets of anaerobic degradation process. The following are some XC and their degrading microbes (Table 2).

Microbial Enzymes Involved in Biodegradation

The major groups of enzymes which assist biodegradation of a wide range of xenobiotics are as follows.

Microbial Oxidoreductases

Oxidoreductases are responsible for oxidization of different types of contaminants and transform them to harmless compound by means of oxidation-reduction

Table 2 List of common microorganism for XC

XC	Microorganisms degrading XC	References
Benzene	*Bacillus* sp.	Lorimor et al. (2001)
PCB	PCB *Rhodococcus* RHA1	Rajan (2005)
Endosulfan compounds	*Mycobacterium* sp.	Sutherland et al. (2002)
Endosulphate compounds	*Arthrobacter* sp.	Weir et al. (2006)
Naphthalene	*Pseudomonas putida*	Muhammad et al. (2007)
Pyrene	*Mycobacterium* PYR-1	Kanaly et al. (2000)

reactions (Karigar and Rao 2011). Oxidoreductases are the potent detoxifier of XC belong to phenolic or anilinic groups with the help of polymerization and binding to humic substances (Park et al. 2006).

Microbial Oxygenase

These enzymes belong to oxidoreductase group (Karigar and Rao 2011). Oxygenase is of two types, monooxygenases and di-oxygenases, based on the number of oxygen atoms for oxidation to happen.

In aerobic biodegradation, oxygenases are the principal enzymes for oxidation reaction. Oxygenases transfer oxygen and use either flavinadenine dinucleotide, nicotinamide adenine dinucleotide or nicotinamide adenine dinucleotide phosphate as the co-substrate for oxidation of the substrates. Various OC are metabolized by oxygenases. These enzymes cleave the aromatic ring of the OC and increase their reactivity and water solubility (Arora et al. 2010). In the bioremediation process, monooxygenases can perform as biocatalysts and have high region selectivity and stereoselectivity on different substrates (Cirino and Arnold 2000; Arora et al. 2010; Yadav et al. 2018). Various reactions are catalysed by monooxygenases such as hydroxylation, de-halogenation, desulphurization, biotransformation and biodegradation of aliphatic and aromatic compounds (Arora et al. 2010).

Monooxygenases catalyse various types of reactions such as biotransformation, hydroxylation, de-halogenation, desulphurization, denitrification, ammonification and biodegradation of various compounds which belong to aliphatic and aromatic family (Arora et al. 2010).

Microbial Dehalogenases

Chlorinated pollutants are the primary target of these enzymes (Copley 1998). Some anaerobic microorganisms are known to use substrates like halogenated compounds as electron acceptors and convert perchloroethylene either dichloroethylene, ethylene or ethane into other forms through this mechanism (Wohlfarth and Diekert 1997; Scholz-Muramatsu et al. 1995; Schumacher and Holliger 1996). Magnuson et al. (1998) partially purified two reductive dehalogenases (perchloroethylene reductive dehalogenase and trichloroethylene reductive dehalogenase) from *Dehalococcoides ethenogenes* strain. The initial enzyme reduces perchloroethylene to trichloroethylene, and the second enzyme is able to reduce trichloroethylene and vinyl chloride.

Phosphotriesterases

These enzymes hydrolyse phosphoesterase bond and mainly act on organophosphate pesticides. Phosphotriesterases decrease the ability of organophosphate pesticides by hydrolysing and reducing toxicity (Theriot and Grunden 2010).

4.1.4 Biodegradation of Plastic Wastes

Plastics are chemically synthesized synthetic polymeric material prepared for human use and having very much similarity to natural resins in many ways. In all aspects of every day's life, it has made its presence due to the versatile nature. Plastics are used for manufacturing different types of products as it is durable, strong, lightweight and cheap (Laist 1987; Pruter 1987). In spite of its vast utility, it creates major environmental hazards due to some unique characteristics such as its buoyant nature, dispersing over long distances, nondegradable and may be sustained in the environment for years (Ryan 1987; Hansen 1990; Goldberg 1995, 1997).

Types of Plastics

Plastics are not only stable and durable but also have suitable thermal and mechanical properties which made its excessive and widespread application in daily life (Rivard et al. 1995). Plastics are generated from monomeric HC. Mostly plastics are produced by chemical alternation of natural materials or raw materials which may be organic or inorganic. Plastics are basically of three types such as thermosetting, elastomers and thermoplastics or thermo-softening plastic based on their physical nature and can be differentiated on the basis of molecular structure. Most of the plastics are thermoplastic type which can be softened and hardened by heating and cooling to give structure. Thermosetting plastics cannot be remodified by heating. Elastomers have the elastic properties of rubber.

Later extensive research work has been started to find out to make biodegradable plastics that could be prototyped for availability to microbial attack in a suitable environment. Biodegradable plastics come up with new possibilities for rejuvenated means of WM approach, as these plastics are formulated to degrade under certain environmental conditions or in biological way of waste treatment equipment (Augusta et al. 1992; Witt et al. 1997). Biodegradable plastics are developed successfully for the past few decades due to its similarity with synthetic plastics. The most significant biodegradable plastic is polyhydroxyalkanoates and polyhydroxybutyrate. Polyhydroxyalkanoates are manufactured from renewable substances, and it is biodegradable and biocompatible in nature. The different types of plastics with features commonly used and their application are shown in Tables 3, 4 and 5, respectively.

Hazards of Plastics

Plastics are almost nondegradable and vastly dumped after being used. Because of this, extensive application of plastic can cause severe environmental hazard to different ecosystems. Terrestrial and marine habitats are significantly hampered due to the accumulation of plastic materials. Disposal of plastic is a major concern due its high production and wide usage. Groundwater ecosystem is also hampered by the

Table 3 Different types of plastics with features

Plastic types	Characteristics
Thermosetting	These are hard plastics and have a branched structure. Thermosets can be shaped only once
Thermoplastics/ thermo-softening	Thermoplastics are high molecular weight plastics and flexible at ordinary temperatures. These types of plastics melt to a liquid form upon heating
Elastomers	Elastomers have viscoelasticity properties and less cross-linked structure. Elastomers are capable of recovering original shape if stretched

Table 4 Synthetic plastics and its use

Synthetic plastic	Use
Polypropylene terephthalate	Used in making soft drink and water bottles, etc.
High-density polyethylene	Preparation of water and milk bottles and grocery bags
Polyvinyl chloride	Used to prepare raincoat, shoe soles and electricity pipes
Low-density polyethylene	Preparation of squeezable bottles and lids of flexible container
Polypropylene	Making of disposable syringes, medicine bottles, car batteries and lid of bottles
Polystyrene	Making of disposable plates and cups, laboratory wares, etc.
Polycarbonate	Used in the preparation of beverage bottles and electric casing

Table 5 Biodegradable plastic types and their general application

Biodegradable plastics types	General application
Polyglycolic acid	Used in subcutaneous sutures, surgeries of thoracic and abdominal region
Polyhydroxybutyrate	Use in making of disposable razors and utensils and also have wide medicinal applications like making of bone plate and wound dressings
Polylactic acid	Used in making of paper coatings, packaging materials and compost bags
Polycaprolactone	Used in drug encapsulation, root canal filling and also in tissue engineering
Polyhydroxyalkanoates	Used for wound dressings, spinal fusion cages, sutures, orthopaedic pins, cardiovascular patches, implant materials etc.
Polyhydroxyvalerate	Used in therapeutic drug delivery for cattle and release vehicle for pharmaceutical drugs
Polyvinyl alcohol	Used in laundry detergent, pesticides, etc.
Polyvinyl acetate	Used as adhesives, paper lamination and remoisten tags

adverse effect of chlorinated plastics. Plastic degradation releases a very fatal greenhouse gas, methane, which brings global warming (Hester and Harrison 2011). Marine ecosystem is also effected by plastic pollution as it can cause morbidity to many marine animals. Different studies indicate that many marine animals including sea turtles, cetaceans, zooplankton and sea bird often ingest plastics which are continuously dumped in the aquatic system. When polyvinyl chloride (PVC) is burned, it releases dioxins which are a potent carcinogen and also an immune and reproductive system disrupter. Some plastic-made bottles have bisphenol as a constituent which is demonstrated as a carcinogen and also hamper physiological system of human. For example, bisphenol can initiate diabetes and preterm puberty (Hester and Harrison 2011).

Plastic Biodegradation and Role of Microorganism

Plastics are considered as major solid waste. Disposal of plastic wastes is a major problem nowadays. Plastic is a polymer, and degradation of polymer can be performed in various ways such as thermal, photo-oxidative, mechanochemical, catalytic and biodegradation, based on the nature of the causing agents. Among these biodegradation process has a great potential due to its effectiveness and environment-friendly manner.

Biodegradation is the natural capability of microorganism to initiate degradation process through enzymatic activity (Albertsson et al. 1987). Microorganisms have significant role in degradation and decaying of synthetic and natural plastics (Gu et al. 2000; Meena et al. 2017). The degradation of plastics happens in a slow manner, and different environmental factors are needed in this process such as temperature and pH. Bacteria and fungi are the main degraders of plastics. The biodegradation of plastic involves various subsequent steps, induced by enzymatic reactions; among them hydrolysis is the most important (Schink et al. 1992). Generally biodegradation of polymeric substances is influenced by different factors such as availability of microbial enzymes and suitable abiotic factors.

Microorganisms use the contaminants for their growth, nutrition and reproduction. This is the main reason behind microbial transformation of different contaminants which are organic in nature. Microorganisms get C from OC. C is essential for microorganisms as it acts as a building block for new cell. C is also a source of energy utilized by the microorganisms (Chapelle 1993). Microorganisms responsible for the degradation of various types of plastics are shown in Tables 6, 7 and 8

Factors Affecting Microbial Degradation

The efficiency of microorganism relies upon several factors such as the chemical nature and concentration of the contaminants and pollutants, their accessibility to microbes and most importantly environmental characteristics (Kaplan and Kitts 2004). Significant factors that affect the rate of microbial degradation are of two types: biological factors and environmental factors.

Table 6 Bacteria used in plastic degradation

Sl. no.	Plastic	Bacteria	Reference
1	Polyurethane	*Corynebacterium* sp., *Pseudomonas* sp., *Arthrobacter globiformis*, *Bacillus* sp.	Kay et al. (1991), El-Sayed et al.(1996), Blake and Howard (1998) and Howard et al. (2012)
2	Low-density polyethylene (LDPE)	*Rhodococcus ruber* C208, *Brevibacillus borstelensis* 707, *Rhodococcus ruber* C208, *Staphylococcus epidermidis*, *Bacillus cereus* C1	Chandra and Rustgi (1997), Sharma and Sharma (2004), Hadad et al. (2005), Sivan et al. (2006) and Chatterjee et al. (2010)
3	High-density polyethylene (HDPE)	*Bacillus* sp., *Micrococcus* sp., *Vibrio* sp., *Arthrobacter* sp., *Pseudomonas* sp.	Kumar et al. (2007), Fontanella et al. (2009) and Balasubramanian et al. (2010)
4	Degradable polyethylene	*Rhodococcus rhodochrous* ATCC 29672. *Nocardia steroids* GK 911, *Bacillus mycoides*	Bonhomme et al. (2003) and Seneviratne et al. (2006)
5	Polyethylene bags	*Pseudomonas aeruginosa, Pseudomonas putida*, *Bacillus subtilis*	Nwachukwu et al. (2010)
6	Polyethylene carry bags	*Serratia marcescens*, *Bacillus cereus*, *Pseudomonas aeruginosa*, *Streptococcus aureus*, *Micrococcus lylae*	Aswale and Ade (2009)
7	Degradable plastic	*Pseudomonas* sp., *Micrococcus luteus*, *Bacillus subtilis*, *Streptococcus lactis*, *Proteus vulgaris*	Priyanka and Archana (2011)

4.2 Bioremediation

Bioremediation is a natural process which makes the use of microorganism to remove waste or pollutant from the water and soil. This is an environment-friendly and sustainable method as it involves eco-friendly microbes in treating the solid waste (Kensa 2011). It is of two types:

(1) *In Situ Bioremediation*: Here removal of water or soil is without excavation and transport of contaminants. Biological treatment on surface of the waste is carried out by bacteria. It is the alternative method of treatment of soil and groundwater. In this technique, non-toxic microbes are applied. This type of bioremediation is of three types:
   (a) *Biosparging*
      It is a waste treatment process of the sites having petroleum products like diesel, gasoline and lubricating oil. In this method the concentration of oxygen is increased by injecting the air below groundwater under pressure. The air pressure has to be controlled in a proper way to avoid the liberation of volatile particles to the atmosphere, which leads to air pollution.

Table 7 Fungi in plastic degradation

Sl. no.	Plastic	Fungi	References
1	Polyurethane	*Chaetomium globosum*, *Aspergillus terreus*, *Curvularia senegalensis*, *Fusarium solani*	Boubendir (1993) and Crabbe et al. (1994)
2	Degradable plastic	*Phanerochaete chrysosporium*, *Penicillium* sp., *Aspergillus* sp.	Lee et al. (1991) and Priyanka and Archana (2011)
3	LDPE	*Aspergillus niger, Penicillium* sp., *Chaetomium globosum*, *Pullularia pullulans*, *Fusarium* sp. AF4, *Aspergillus oryzae*	Gilan et al. (2004) and Shah et al. (2009) and Konduri et al. (2011)
4	HDPE	*Aspergillus terreus* MF12, *Trametes* sp.	Balasubramanian et al. (2014) and Iiyoshi et al. (1998)
5	PVC	*Polyporus versicolor*, *Phanerochaete chrysosporium*, *Pleurotus sapidus*, *P. eryngii*, *P. florida*	Kirbas et al. (1999)
6	Disposable plastic films	*Aspergillus flavus*, *Mucor rouxii*	El-Shafei et al. (1998)
7	Polyethylene carry bags	*Phanerochaete chrysosporium, Aspergillus niger*, *A. glaucus*, *Pleurotus ostreatus*	Aswale and Ade (2009)
8	PVC films	*Phanerochaete chrysosporium*, *Lentinus tigrinus*, *Aspergillus niger*, *A. sydowii*	Ali (2011)

Table 8 Actinomycetes used in plastic degradation

Sl. no.	Plastic	Actinomycetes	Reference
1	Polyurethane	*Acinetobacter calcoaceticus*, *A. gerneri*	Howard et al. (2012)
2	Polyethylene	*Streptomyces* sp., *Sporichthya* sp. *Actinoplanes* sp.	Sathya et al. (2012)
3	Disposable plastic films	*Streptomyces* sp.	El-Shafei et al. (1998)
4	LDPE powder	*Streptomyces* KU5, *Streptomyces* KU1, *Streptomyces* KU6	Usha et al. (2011)

(b) *Bioventing*

It is the process in which waste compounds are degraded aerobically. Bioventing is used to treat different solid wastes generated from oil reservoirs during extraction of gasoline and petroleum. In this process the contaminated site is injected by oxygen and nutrients like phosphorus and N to increase the rate of removal process.

(c) *Bioaugmentation*

Here cultured microorganisms are added at the polluted site for the purpose of biodegradation of contaminants of specific environment. This process makes sure that the microorganisms also break down contaminants present in the groundwater and soil to non-toxic compound.

(2) *Ex Situ Bioremediation***:** It describes the removal of the contaminated soil or water for remedy process. The following are the types of ex situ bioremediation:
   (i) *Composting***:** Composting is an aerobic method where contaminated soil is combined with harmless organic amendments. Organic amendments help to grow microbial population in high quantity.
   (ii) *Land farming***:** It is a bioremediation technology wherein contaminated soil is mixed with soil amendments, and after that the mixture are tilled into the earth. The main target is to enhance indigenous biodegradative microorganisms for degradation of contaminants aerobically.
   (iii) *Bio-piling***:** It is a hybrid technology using both land farming and composting. This technique gives a suitable environment for growing both aerobic and anaerobic microorganisms. Bio-piles are applied to eliminate petroleum constituents' concentrations with the help of biodegradation.

4.2.1 Heavy Metal Bioremediation

Heavy metals are generally considered as metals having relatively high densities and atomic weight. Few heavy metals like silver (Ag), copper (Cu), cadmium (Cd), lead (Pb), zinc (Zn) and chromium (Cr) are considered as heavy metals because of their toxicity properties. The existence of heavy metals in the environment can contaminate the soil and groundwater through the process of leaching. Toxic metals may enter feeding relationships among organisms through water engendering inauspicious consequences on the overall living things. Various microorganisms like bacteria, algae and fungi act as a bio-absorbent in degradation of the metals. Yeasts have been reported of having a significant role in toxic heavy metal elimination from the environment. Some pioneer research work indicate that yeasts are efficient and superior heavy metal accumulator such as Cu(II), Ni(II), Co(II), Cd(II) and Mg(II) compared to certain bacteria (Wang and Chen 2006). Bahafid et al. (2011, 2012) reported that *Pichia anomala* is able to eliminate Cr (VI) and cells (live or dead) of three yeasts species: *Cyberlindnera, Tropicalis*, *Cyberlindnera fabianii* and *Wickerhamomyces anomalus* are good bio-absorbers of Cr(VI).

Ksheminska et al. (2006) reported that *Saccharomyces cerevisiae*, *P. guilliermondii*, *Rhodotorula pilimanae*, *Yarrowia lipolytica* and *Hansenula polymorpha* are able to remove Cr(VI) to Cr(III). Several studies have reported that the immobilized cell of yeast *Schizosaccharomyces pombe* is efficient to remove copper (SaiSubhashini et al. 2011). Several species of *Chlorella* sp., *Anabaena* sp., *Westiellopsis prolifica*, *Stigeoclonium tenue* and marine algae have been used for heavy metal removal, and more importantly these organisms have effective heavy metal tolerance ability (Dwivedi 2012). Algae apply adsorption mechanism for metal uptake. Brown algae are also considered for heavy metal biosorption by a number of cell wall components such as alginate and fucoidan. The continuous cultures of microalga *Scenedesmus incrassatulus* has been demonstrated for Cr(VI),

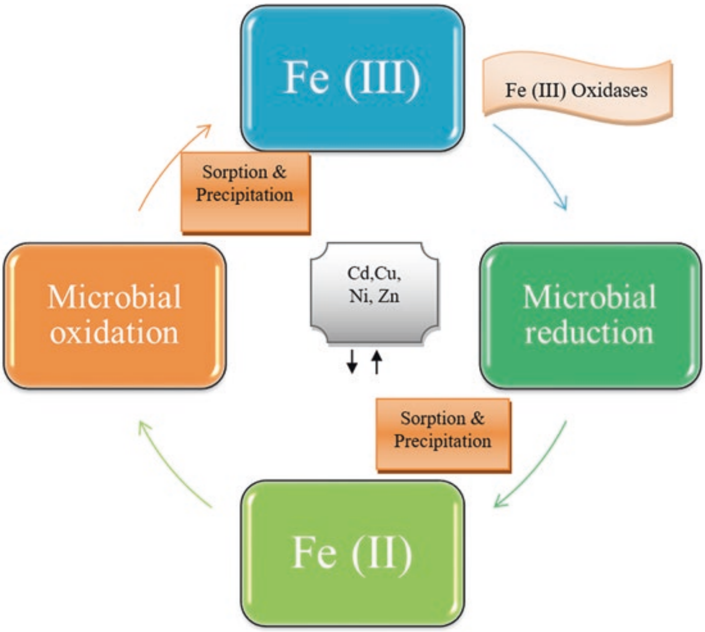

Fig. 5 Schematic view of heavy metal bioremediation. (Source: https://water.usgs.gov/nrp/microbiology)

Cd(II) and Cu(II) removal (Peña-Castro et al. 2004). Green algae *Chlorella sorokiniana* have also been reported as bioremediator of Cr(III) (Akhtar et al. 2008). Schematic view of bioremediation of heavy metals is shown in Fig. 5.

Microorganisms have developed various ways by which they are able to protect themselves from the toxic effect of heavy metals. Some of those ways are oxidation, reduction, adsorption, uptake and methylation. For example, bacterial species such as *Alcaligenes faecalis*, *Bacillus pumilus*, *Bacillus* sp. and *Pseudomonas aeruginosa* utilize bio-methylation to form methylmercury from mercury, Hg (II) (De Jaysankar et al. 2008; Ashoka et al. 2017). In addition to methylation reactions, acidophilic bacteria *Acidithiobacillus ferrooxidans* (Takeuchi and Sugio 2006) and sulphur-oxidizing bacteria (White et al. 1998) have been reported to leach high concentrations of heavy metals like As, Cd, Cu, Co and Zn from polluted site.

4.2.2 Rubber Waste Bioremediation

Rubber is considered as a solid waste and consists of synthetic material. Unscientific method of disposing rubber is by burning it. Burning of rubber generates huge quantity of hazardous elements like C monoxide which has devastating effect on the environment (Adhikari et al. 2000). Due to its physical composition, it can neither degrade nor recycle easily (Conesa et al. 2004). Naturally rubber is degraded very slowly because rubber has zinc oxides which are responsible for the inhibition of growth of naturally evolved bacteria and sulphur-oxidizing bacteria (Zabaniotou and Stavropoulos 2003). To overcome this problem, *Recinicium bicolour* (fungi) is used to eliminate the entire harmful and environmentally unfriendly ingredient of rubber, and thereafter the rubber can be treated with sulphur-reducing or sulphur-oxidizing bacteria like *Pyrococcus furiosus* and *Thiobacillus ferrooxidans* for devulcanization. After these treatments the rubbers can be easily recycled (Keri et al. 2008). So by regulated kindling, effective management of rubber waster can be achieved (Conesa et al. 2004).

4.2.3 Bioremediation of Agricultural Waste

Agricultural wastes are outputs of production and processing of various agricultural products which are beneficial to human. Economic values of these products are less valuable than the cost of collection, transportation and processing to make them beneficial for use. Generally, agricultural wastes are produced from a number of sources such as cultivation, livestock and aquaculture. Effective disposal mechanism and environment-favourable operation mechanism of the wastes have received a prime concern globally. Hence a lot of attention has been put forward to devolve potential and cost-effective machinery to metamorphose these wholesome wastes into valuable products for achieving endurable environments and development. In this regard microorganism plays a significant role in OM degradation, and the role of earthworm is also considerable as it propels the procedure and transmutes the organic activity (Dominguez 2004).

4.3 Biotransformation

Biotransformation is a transformation of toxic compounds into less persistence and less toxic form. Bacteria and fungi are the major groups of microorganisms, and their enzymes are involved in this process. Microorganism cells are crucial for biotransformation due to some causes such as:

- *Surface-volume ratio*: Surface-volume ratio is high in case of microorganism-mediated biotransformation.
- *Rate of microbial cell growth*: Microbial cells have high growth rate which minimizes biomass transformation duration.
- *Rate of metabolism*: Rate of metabolism in microorganism is very high which is needed for efficient transformation.
- *Sterile condition*: In order to make effective biotransformation, it is necessary to maintain sterile condition of the microorganism (Hegazy et al. 2015).

4.3.1 Biotransformation of Pollutants

In the present day, use of microorganism in biotransformation of different pollutants have harvest much interest to mitigate the polluted environment (Pajouhesh and George 2005). The bacterial genera which have been associated potentially with biotransformation process of varieties of contaminated wastes can be aerobic or anaerobic types. Examples of aerobic types are *Escherichia* sp., *Micrococcus* sp., *Pseudomonas* sp., *Bacillus* sp., *Rhodococcus* sp., *Gordonia* sp. and *Moraxella* sp., whereas *Methanosaeta* sp., *Methanospirillum* sp., *Desulfotomaculum* sp., *Pelatomaculum* sp., *Syntrophus* sp., *Syntrophobacter* sp. and *Desulfovibrio* sp. belong to anaerobic types (Chowdhury et al. 2008). *Mycobacterium vaccae* has been reported to catabolize benzene, ethylbenzene, propylbenzene, acetone, cyclohexane and dioxane. On the other hand *Pseudomonas* sp. and *Bacillus* sp. have been reported to degrade PCB effectively. Some strains of bacteria such as *Pseudomonas* sp., *Acetobacter* sp. and *Klebsiella* sp. are able to biofix carcinogenic azo compounds. Studies suggest that two strains of *Pseudomonas* such as BCb12/1 and BCb12/3 are exceptionally degrading low-ethoxylated nonylphenol polyethoxylates (DiGioia et al. 2008).

Several methanogens such as *Syntrophobacter fumaroxidens* and *Methanospirillum hungatei* which are anaerobic in nature have been reported to degrade phthalate compound (Qu et al. 2004; Zhang and Bennet 2005). A promising research reported that pollutants which have the pentafluorosulfanyl (SF_5) functional group have been bio-transformed by *Pseudomonas knackmussii* and *P. pseudoalcaligenes* KF707 and *Cunninghamella elegans* (Kavanagh et al. 2014).

4.3.2 Biotransformation of Petroleum

Petroleum is the principal means of propulsion in industry and livelihood (Mathew 2012). However, HC contamination related to the petrochemical industry has a place in the foremost environmental issues right now (Das and Chandran 2011; Dadhich et al. 2015). Soil and water are polluted due to leaks and accidental release of contaminants. Petroleum is a potent carcinogenic and neurotoxic to all biota (O Peter 2011).

In order to remediate the contaminated soil and water, various chemical and mechanical methods are available, but utilization of microorganism in biotransformation process is the most effective method for detoxification of the pollutants as it is environment-friendly and cost-effective, and the most important part is that it leads to complete mineralization. Many aquatic and marine microfloras have been reported in the oil spill biodegradation (McGenity et al. 2012). Bacteria, yeast and fungi are the principal microorganisms for petroleum biotransformation (Atlas 1981). *Sphingomonas* sp. has been reported to degrade polyaromatic HC (Daugulis and McCracken 2003).

Some bacterial genera such as *Mycobacterium* sp., *Arthrobacter* sp., *Rhodococcus* sp. and *Pseudomonas* sp. have been reported to degrade petroleum HC very effectively. Several other microorganisms such as *Gordonia* sp., *Brevibacterium* sp., *Corynebacterium* sp., *Flavobacterium* sp., *Pseudomonas fluorescens*, *P. aeruginosa*, *Actinocorallia* sp., *Klebsiella* sp., Rhizobium sp., *Bacillus* sp. and *Alcaligenes* sp., *Aeromicrobium* sp., *Dietzia* sp., *Burkholderia* sp. and *Mycobacterium* sp. have been extracted from petroleum-polluted zone and are reported to degrade HC very efficiently (Chaillan et al. 2004). *Cephalosporium* sp., *Aspergillus* sp., *Penicillium* sp., *Neosartorya* sp., *Talaromyces* sp. and *Amorphoteca* sp. are the fungal microorganisms found in petroleum-contaminated sites and have been reported in oil spill bioremediation (Koul and Fulekar 2013).

4.3.3 Microorganism and Waste Water Management

WW management chemical and biological are the two principal treatment methods to clean up WW impurities. In comparison with chemical treatment, biological treatment has obtained more potentiality due to many reasons such as biological treatment is more cost-effective and environmentally sustainable. Microorganisms are of major importance in different WW treatments like industrial, agricultural and in aquaculture. Microbes efficiently eliminate and degrade different toxic materials such as ammonia, nitrite, hydrogen sulphide, etc. The role of microorganisms particularly bacteria and protozoa in WW treatment system is very significant as these organism are potent degrader of N and phosphorus.

5 Roles of Microorganisms in Wastewater Treatment Systems

Bacteria

Bacteria are of greatest importance in the treatment of WW. Most of them are facultatively living in either aerobic or anaerobic conditions (Spellman 1997; Absar 2005). In WW treatment systems, both autotrophic and heterotrophic bacteria are found, but predominant ones are the heterotrophic bacteria. Generally, heterotrophic bacteria use the carbonaceous OM as their energy source in WW effluent. The obtained energy is utilized for new progeny cell production and energy release by the conversion of organic substances and water. *Achromobacter* sp., *Alcaligenes* sp., *Arthrobacter* sp., *Citramonas* sp., *Flavobacterium* sp., *Pseudomonas* sp., *Zoogloe* sp. and *Acinetobacter* sp. are some important bacteria found in WW treatment system (Oehmen et al. 2007; EPA 1996). Bacteria are the key microorganisms which are able to stabilize influent wastes in WW treatment systems. The interesting thing is that majority of the bacteria are known to form peculiar body mass that are clump of bacteria that degrade waste and serve as absorption site of waste also. Filaments of filamentous bacteria help the peculiar body to grow and prevent the splinter action in the treatment process. When filamentous bacteria are found in excessive quantity or stretch, they can cause settlement problems (Paillard et al. 2005).

Alga

Some types of algae that can be found in WW include *Euglena* sp., *Chlamydomonas* sp. and *Oscillatoria* sp. Algae is a potent organism to purify WW biologically as they are able to accumulate heavy metals, pesticides and organic and inorganic pollutants. Over the years, microalgae have gained a lot of importance in the treatment of WW (Lloyd and Frederick 2000).

Fungi

Fungi are also found in WW treatment systems. Fungi are multicellular creatures that are also an integral part of the sewage treatment. If fungi are cultured with bacteria under some environmental criteria, they can compete with bacteria and also able to metabolize compounds that are organic in nature. Few types of fungi are able to oxidize ammonia to nitrite. *Sphaerotilus natans* and *Zoogloea* sp. are the most common sewage fungus organisms (Painter 1970; LeChevallier and Au 2004). Varieties of filamentous fungi are found naturally in WW treatment systems which can also metabolize organic substances. Different types of fungi species, like *Aspergillus* sp., *Penicillium* sp., *Fusarium* sp. and *Absidia* sp., have been used to remove C and nutrient sources in WW (Akpor et al. 2013). Some fungi are also demonstrated to have the capacity to break down OM present in the sludge system effectively. In a system with low pH, the main role of the fungi is the breakdown of OM where bacterial growth is inhibited. Moreover, some fungi use their fungal hyphae for trapping and adsorbing suspended solids to mitigate their energy and nutrient prerequisite. It has been reported that some filamentous fungi secrete some enzymes which help to degrade the substrates during WW treatment (Molla et al. 2004; Buragohain et al. 2017).

6 Conclusion

Preservation and sustainability of the environment is recognized at the highest levels of priority that require critical attention globally because it is vital for progressing into the future. To ensure sustainability, management of waste, preservation of NR and biodiversity and treatment of contaminant and pollutants are the key areas that really need a focus of priority. Nowadays safeguarding environment from deterioration is not only dismissal of the contaminants and pollutants but also recycling and reuse of hazardous substances by transforming different wastes to prosperity of useful things in an aesthetic and environment-friendly manners. Interest in the use of different microorganisms has intensified and got a priority in the recent scenario as humanity struggle to achieve sustainable manner to tidy up polluted environments and waste. With the advent of biotechnology, the potentiality of microorganisms for selected uses has received increased attention and speculation. Microorganisms are unique and often unpredictable in nature. Microorganisms can be used as an effective agent for solving many environment related problems. The scientific and trustable use of microbes is unavoidably illecebrous and figures out a spectacular evolution of research and innovative tools to provide an effective way to shield our planet and modern means of biological WM and environmental monitoring. At last it can be concluded that the use of microorganisms and microbiological techniques has opened up new vistas in the field of sustainable development particularly in the areas of environment and other important environment-related issues.

7 Future Prospective

WM is now becoming very important throughout the world as well as in India as it is an integral part towards sustainable environment and development. India has immense opportunity, and it is very true to say that the success is very few. So there are certain areas that should be answered to find out the meaningful future of WM. The questions are:

1. Growing importance of WM all over the world.
2. Identification of stakeholders involved in the WM process.
3. Recent trends and innovation in WM.
4. The challenges and best solution of WM.

Rapid urbanization and industrialization have put tremendous pressure on WM throughout the world. So the principle behind the WM should be based on precaution and sustainable development. The key for effective WM has to be identified to ensure waste separation from the source and also have to pass through different modes of recycling and recovery before depositing in the landfills. Biotechnology and microorganisms can be used effectively in WM, hence more research and knowledge would be developed related to the role and application of biotechnology and microorganisms in WM. Making energy from waste and waste to compost would minimize waste quantity. It is believed that if biodegradation part of waste is somehow separated, the challenges are reduced effectively. The future aim should be the development and redraw a long-term vision and strategy to cope up with the changing lifestyles. Community participation and development of knowledge towards sustainability have a direct effect on effective WM. Community has to develop the idea of recycling and reuse from very low scale to large scale.

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A Contemplation On Pitlakes of Raniganj Coalfield Area: West Bengal, India

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Abstract

Pitlakes (PLs) form when surface mines close and open pits filled with water, either through groundwater recharge, surface water diversion or active pumping. The primary goal of this study was to prepare an inventory of PL in Raniganj coalfield (RCF), West Bengal, India, along with the status of water quality in these PLs for promoting sustainable utilization of the PL resources for socioeconomic development of the local stakeholders in due course of time. A total of 40 PLs were enumerated and characterized to determine their nature, position, depth, area and comparative account in RCF during the period of 2014–2017. A consecutive 2-year study of physicochemical parameters of water and soil was recorded at 27 selected mine PLs to understand its quality. A total of 30 species belonging to 21 families of frequent hydrophytes/marginal plant species dominating these PLs were observed. successional stages of plant species were noticed and grouped in accordance with their growth pattern. During the study period, the 15 most frequently cultured/naturally occurred fish species under 4 orders, 5 families and 14 genera were collected and identified from the PL. After the analysis of PL water quality and questionnaire survey of the local stakeholders, we have recorded that developmental pisciculture project can be started in 25 PLs. PLs aged over 20–30 years turned naturally into wetland ecosystem harbouring a good amount of aquatic biota, excellent water quality and stabilized embankment. Sixty species of wetland birds (with terrestrial counterparts in the adjoining floral habitat) belonging to 15 orders and 34 families were recorded. The main findings of this work was to explore the ecological health status, study the ecological census of PL in RCF, exploration of ecological health status of the PL on, accessibility of the biological resources of PL.

Keywords

Pitlakes · Water quality · Soil quality · Developmental activity · Floral succession

Abbreviations

AMD	Acid mine drainage
BOD	Biochemical oxygen demand
DA	Discriminant analysis
ECL	Eastern Coalfields Limited
FT	Foot
Ha	Hectare
Km	Kilometre
LULC	Land use and land cover
N	Nitrogen
OCP	Open-cast pit
OC	Organic carbon

PCA	Principal component analysis
PL	Pitlake(s)
RCF	Raniganj Coalfield
SO_4^-	Sulphates
TDS	Total dissolved solid

1 Introduction

All surface mining process creates drastic changes in the landscape. They result in the formation of large overburden dumps, huge voids and pitlake (PL) ecosystems in the mining sites (Kumar et al. 2017; Raj et al. 2018). By definition a PL is a lake that forms by flooding of an excavated mining pit. PL differs physically from natural lakes in having markedly higher relative depths. During active mining, surface water is diverted around open pits, and perimeter and dewatering pumps are used to control groundwater inflow and direct rainfall. PL forms when the pumps are shut off and post-mining drainage of surface/groundwater and precipitation begin to accumulate inside the inactive pit. PL can form in open-cut mining pits, which extend below the groundwater table. Pits from mining of chemically inert materials tend to mirror the geochemistry of their surroundings, and lakes that form in such pits do not produce pits with various physical, geochemical and ecological mine impoundments, such as tailings ponds, are not included in the above definition. PL waters are typically contaminated with metals, metalloids, saline or acidic/alkaline and rarely approach natural waterbody chemistry (Dimitrakopoulos et al. 2016).

Physically, PL has unique bathymetries, is often strongly wind sheltered and has very small catchments. Nevertheless, PL waters often constitute a vast resource but of limited beneficial use (due to water quality issues), with a potential to contaminate regional surface and groundwater resources. Water in PL has the potential to be useful for a range of purposes in characteristically hot, dry climatic regions in India with relatively few natural water bodies. Their value as resources for recreation, fisheries, water supply and wildlife habitat depends mostly on their topography and their safety. PL may have long-term benefits as a water source for industrial activities rather than relying on natural systems (Palit et al. 2017; Ram and Meena 2014).

Ecological restoration and ecosystem management is an essential component of any habitat conservation (Banerjee et al. 2018; Jhariya et al. 2018a, b). Coal mining started in the Raniganj Coalfield (RCF) area in 1774 during the British East India period. The RCF covers an area of 1530 sq. kilometre (Km), containing about 1306 sq. km of coal-bearing land. In West Bengal, especially in RCF region, opencast mining has become increasingly common over the last few decades through changes in excavation technology and ore economics. Moreover, such operations frequently leave a legacy of open mine pits once mining ceases. The lack of knowledge on PL continues to hinder their proper management. Information on PL occurrence, distribution, bio-profile, water quality and usefulness aspects is not nationally collated and requires immediate and perpetual attention from both mining companies and regulating authority (Palit et al. 2014). Lack of a readily available database pertaining to PL occurrence, distribution and water quality fails to promote both mining companies and communities in RCF region in assessing the potential of these water resources.

PL ecosystems are not only ecologically threatened and critical aquatic landscapes but also a source of potential biological resources for the future. They may support a rich biodiversity and high abundance of animal and plant species, many of them threatened on a local or worldwide basis (Maltby and Barker 2009). The lack of knowledge on PL continues to hinder their proper management. Wetland and freshwater systems such as PL are important for the provision of environmental and ecological services (MEA 2005) in developing countries that result from their varied bio-geo-chemical functioning, ranging from fresh water to provision of services economically useful to human populations, for example, food provision from fishing and income generation via ecotourism.

However, recent investigations on aquatic systems have highlighted the fact of continued decline in aquatic species and degradation of wetland and freshwater habitats across the world (Hassall 2014). One of the reasons for human failure to use the natural environment and resources of freshwater ecosystems in a sustainable way is because the long-term benefits to be derived from such sustainable use are not always as obvious as the perceived short-term benefits from economic development which destroys or damages the freshwater habitat.

Freshwater resources of the world are a repository of rich biodiversity (Murphy et al. 2003; Dudgeon et al. 2006; Schmidt-Mumm and Janauer 2014; Clarke 2015). They support many key ecological processes (Cereghino et al. 2014) and provide a number of benefits free of cost to the human society. Studies on freshwater resources in connection with their ecology, biodiversity, multipurpose usages and conservation have investigated in many different parts of the world (Janauer 2012; Gupta and Palit 2014; Turak et al. 2017; Inomata et al. 2018; Dhakal et al. 2016).

Thus quality assessments of selected PL in RCF have been carried out during 2014–2017 in order to assess the overall hydrological conditions, bio-profile and efficacy to evolve strategies for an ecological restoration, conservation and management.

2 Genesis of Pitlakes

2.1 Background

Coal mining started in the RCF area in 1774 during the British East India period. The RCF covers an area of 1530 sq. km, containing about 1306 sq. km of coal-bearing land. All surface mining process creates drastic changes in the landscape. They result in the formation of large overburden dumps, huge voids and PL ecosystems in the mining sites.

2.2 Pitlake Formations

Open-cast mining operations have become a common practice over the last few decades in India, as a method of extracting commercially useful ore found near the surface. Since backfilling is normally unfeasible practically or economically, an open pit after completion of extraction operations is left which is known as mine void. After mine operations are discontinued and dewatering ceases, most of those that extend below the natural groundwater table, fill by inflow of groundwater, direct rainfall, and runoff from adjacent drainage basins and the void catchment. Natural filling may take many years to complete. To reduce oxidation of mining waste and wall rocks, to inhibit the activity of acidophilic sulphur-oxidizing bacteria and to promote anoxic conditions at the lake bottoms which may minimize the formation of acids and dissolved metals, some PLs are rapidly filled with stream or river diversions. The water qualities in such PL depend on the filling water and geological catchments and are highly variable. Although the water level may continue to fluctuate as it equilibrates or as climate and local groundwater levels alter, once containing water, the empty mine void has now become a PL. The number of future open-cut mines is likely to continue with current and predicted demands for minerals and energy, the global financial crisis notwithstanding. Except for those in the most arid areas, deep open-cut mines are likely to develop PL when mining operations end. Given the large number of PL that will form worldwide and the large volume of water they will contain, the quality of the water in these lakes will be of profound importance, especially in areas with scarce water resources (Blanchette and Lund 2016).

2.3 Pitlake Characteristics

PL differs physically from natural lakes in having a markedly higher ratio of depth to surface area. This is described by percent relative depth, which is defined as the percentage of a lake's maximum depth compared to its width calculated from its surface area by assuming the lake is approximately circular. A typical natural lake has a relative depth of less than 2%, although some may exceed 5%. PL commonly has relative depths between 10% and 40% (Doyle and Davies 1999). This causes PL to easily stratify with the consequential changes in chemical characteristics with depth.

Total dissolved solids (TDS) and electrolytic conductivity tend to increase with depth; values near the bottom are often several times those at the surface. The hypolimnion (lower stratum) of a stratified lake has the tendency to contain low dissolved oxygen concentrations, if enough oxygen demand (chemical and/or biological) is high enough. The existence of a sub-oxic or anoxic (no oxygen) layer in a PL can have significant effects on the lake's chemical and biological characteristics and thus on its potential for remediation. Where pit sides are battered for public access or to promote development of riparian (fringing vegetation) zones, deep pits will still have a bathymetry unlike natural lakes with steep sides below the battering.

As PL typically has limited catchments, inflows of surface water tend to be small which may be useful in preventing worsening water quality from exposed geologies.

However, where exposed geologies are not problematic, it may be desirable for PL water quality to capture clean surface waters, and small catchments may limit this. PL water quality can be highly variable, particularly for acidity, salinity, hardness and metal concentrations which are primarily governed by the PL catchment hydrology and geochemistry (Miller et al. 1996). For example, PL water quality may become acidic, through oxidation of reactive iron-bearing geologies as acid mine drainage (AMD) (Klapper and Geller 2002; Hinwood et al. 2011, 2012; Verma et al. 2015). Such acidic mine waters are often toxic to aquatic biota (Spry and Wiener 1991; Doyle and Davies 1999; Storer et al. 2002; Stephens and Ingram 2006).

PL waters affected by salinity and acidity may also adversely influence nearby and regional groundwater resources and receiving environments, e.g., wetlands with contaminated plumes from flow-through PL extending large distances down-gradient. The extent of such an impact may vary from insignificant in low hydraulic conductivity rocks and groundwater systems already saline to considerable in high hydraulic conductivity rocks and naturally low-salinity groundwater environments (Commander et al. 1994; Johnson and Wright 2003).

The majority of PL studies conducted in India have focussed on physical and chemical characteristics of water quality. These studies have demonstrated that PL water quality is influenced by many factors including climate, groundwater quality, depth, pit filling method and local mineralogy. Many PLs contain high levels of acid, sulphate and dissolved metals/metalloids. The chemical characteristics of a lake depend on the alkalinity of the local groundwater, the composition of the wall rocks, the chemistry of the surrounding vadose zone and the quality and quantity of runoff from the surrounding land (Plumlee et al. 1992; Davis et al. 1993). Rock that is exposed to oxidizing conditions during dewatering can be a major source of acid, even though it lies below the water table before mining operations begin and after the lake fills (Miller et al. 1996). The most common set of reactions producing acidity in mine lakes is the oxidation of PL resource sulphide and iron in pyrite (FeS_2) in the following two reactions (Castro and Moore 1997):

1. $FeS^2 + 7/2O^2(aq) + H_2O \rightarrow Fe^{2+} + 2SO_4{}^{2-} + 2H^+$
2. $Fe^{2+} + 1/4O^2(aq) + 5/2H^2O \rightarrow Fe(OH)^3 + 2H^+$

In natural systems pH is typically buffered by a carbonate buffer system (at pH of 6–8.5); however PLs of lower pH are often buffered by aluminium complexes (pH 4.5–5.5) or iron complexes (pH 2.0–4.0).

2.4 Land Use Pattern of Adjoining Areas

Several studies on RCF area revealed that it is free from AMD (Ghosh et al. 1984, 2005; Tiwary and Dhar 1994). Different studies on limnological parameters depicted the high conductivity, total suspended solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), sulphates (SO_4^-), etc., in mine water of this area (Ghosh 1990; Tiwary and Dhar 1994; Singh et al. 2009, 2010). Few records are available on assessment of water quality and seasonal variations of the Indian coal PL (Ghosh et al. 2005; Singh et al. 2009, 2010; Mukherjee et al. 2013; Palit et al. 2017; Meena et al. 2018).

Mining operation, undoubtedly, has brought wealth and employment opportunity in the area but simultaneously has led to extensive environmental degradation and erosion of traditional values in the society (Kumar et al. 2016; Jhariya et al. 2013, 2016). The rate and the intensity of land use and land cover change are very high in developing new mining area because of various human activities. Mining of coal, both surface and subsurface, causes enormous damage to the flora, fauna, hydrological relations and soil biological properties of the systems. Destruction of forests during mining operation is invariably accompanied by an extensive damage and loss to the system. A detailed understanding of the environmental impact of coal mining on changes in land use/land cover pattern and fragmentation of time and space is a prerequisite for the district.

2.5 Present Scenario of Pitlakes and Its Adjoining Areas

The current scenario of the PL in this region is generated for the first time. Further extensive research, investigation, seasonal monitoring and pilot-scale study with socioeconomic purview in the next phase of the study will produce valuable research findings. However, recent investigations on aquatic systems have highlighted the fact of continued decline in aquatic species and degradation of wetland and freshwater habitats across the world (Hassall and Anderson 2015).

One of the reasons for human failure to use the natural environment and resources of freshwater ecosystems in a sustainable way is because the long-term benefits to be derived from such sustainable use are not always as obvious as the perceived short-term benefits from economic development which destroys or damages the freshwater habitat. Thus, ecological restoration and ecosystem management is an essential component of any habitat conservation.

PL ecosystems are not only ecologically threatened and critical aquatic landscapes but also a source of potential biological resources for the future. They support rich biodiversity and high abundance of animal and plant species, many of them threatened on a local or worldwide basis (Maltby and Barker 2009). The lack of knowledge on PL continues to hinder their proper management which is also observed under the present investigation. Wetland and freshwater systems such as PL are important for the provision of environmental and ecological services (Millennium Ecosystem Assessment 2005) in developing countries that result from their varied bio-geo-chemical functioning, ranging from fresh water to provision of services economically useful to human populations, for example, food provision from fishing and income generation via ecotourism. The present work would have valuable practical applications since PLs play an important role in the ecosystem functioning and hydrology of the area. They provide habitat for migratory birds, fisheries, water plants, animals and microbes.

In view of this, the present work is of clear importance especially for policy designers. The findings of UPAR1 would contribute to the following outputs for conservation of PL in RCF-WB:

1. This revealed the current condition of the PL of the target region but also provides necessary guidelines for implementation of PL management/livelihood generation programmes for the benefit of stakeholders inhabiting the area.
2. After successful completion of this research study, it is now possible to provide data on the ecology, biodiversity and environmental values of the PL in RCF-WB. The research thus contributed to the development of decision support systems for better conservation, management and sustainable use of wetlands to promote the key message of the Ramsar Convention's (1971) mission to achieve "the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world."

2.6 Change Analysis in Different Land Use/Land Cover

Land use and land cover (LULC) are categorized into nine classes; these are crop area, moist fallow, land surface deep waterbody (pond and abandon quarry), river water, river sand, dense forest, open forest, settlement and quarry. The result of the change analysis shows that there are directly or indirectly influences on different land use and land cover due to the impact of mining activity. According to the study, the decrease of the LULC is 298.16 sq. km of the moist fallow, 53 sq. km of the dense forest, 117.37 sq. km of the open forest, 12.71 sq. km of the river water and 1.27 sq. km of the river sand, and the increase of the LULC is 91.52 sq. km of the crop area, 88.13 sq. km of the surface deep waterbody, 103.81 sq. km of the settlement and 199.99 sq. km of the quarry area that has changed due to the mining activity during 1990–2014. More than 90 sq. km area of moist fallow, 2 sq. km area of dense forest and 10 sq. km of open forest have been converted into the open-cast mining during that period.

An elaborative description of 40 PLs of RCF was tabulated in Table 1. Overall PL was classified with its age series. Area and depth of each PL was noticed and documented. According to age range, each PL is grouped into six classes. Class 1 has those PLs that belong to their age of 1–20 years. In such manner classes 03, 06, 07, 18, 19, 20, 22, 25, 28, 35, 39 and 19, 7 and 1 consist of the PLs having their age range of 21–40, 41–60 and 61–80, respectively. Areas of most of the PLs were in ranged from 1 to 150 bighas. Dalmia, Alkusa Gopalpur and Kumardihi Old PLs were ranged from 150 to 200 bighas. The areas of Nimcha Damali Harabanga, Nimcha Harabanga and Gunjan Ecological Park PLs have the largest area such as 250 bighas, 300 bighas and 250–300 bighas, respectively. Ramnagar (400 foot) was the deepest PL found in RCF. Kumardihi Old, Vatas 1 and Vatas 2 were the second deepest PLs. The depthness of Katapahari PL was less in comparison to all other PLs of RCF. All PLs were ranged within 40–400 ft in accordance with their depth.

Table 1 An account of genesis of PL of RCF, West Bengal, India

Serial no.	Name of the PL	Origin of PL (years)	Area (bigha)	Depth (feet)	Area of mining	Block	Nearest village/town
PL01	Chora PL	30	50	80	Bankola	Pandabeswar	Chora
PL02	Joyalbhanga 1 PL	35	>80	70	Bankola	Pandabeswar	Joyalbhanga
PL03	Vatas PL	20	70–80	300	Sripur	Baraboni	Vatas
PL04	Katapahari PL	50	50–60	100	Sripur	Baraboni	Katapahari
PL05	Amdia PL	40	80	250	Salanpur	Salanpur	Amdiha
PL06	Samdi PL	20	>40	250	Salanpur	Salanpur	Samdi
PL07	Dalmia PL	30	162	250	Salanpur	Salanpur	Sikhdaspur
PL08	Bamna PL	50	30	100	Salanpur	Salanpur	Bodra
PL09	Bonbedi PL	60	>50	250	Salanpur	Salanpur	Bonbedi
PL10	Alkusa Gopalpur PL	70	>150	250	Salanpur	Salanpur	Alkusa
PL11	Sikhdaspur PL	20	50	70	Salanpur	Salanpur	Sikhdaspur
PL12	Jambad 5 PL	70	>70	150	Kajora	Andal	Benedi
PL13	Jambad 4 PL	60	50	120	Kajora	Andal	Benedi
PL14	Jambad Bottom-Up PL	50	>50	100	Kajora	Andal	Benedi
PL15	Western Kajora PL	40	125	40	Kajora	Andal	Kajora
PL16	Atewal PL	40	70	60	Kajora	Andal	Jogrambati
PL17	Khadan Kali PL	40	125	40	Kajora	Andal	Polashbon
PL18	Babuisolsib Mandir PL	15	125–126	60	Kajora	Andal	Babuisol
PL19	Ramnagar PL	10	100	400	Sodepur	Pandabeswar	Ramnagar
PL20	Belpahari Kottadihi PL	10	1	40	Pandabeswar	Pandabeswar	Belpahari
PL21	Dalurbandh PL	40	>100	100	Pandabeswar	Pandabeswar	Dalurbandh
PL22	Nagrakonda PL	3	50	100	Pandabeswar	Pandabeswar	Nagrakonda
PL23	Pathaldanga PL	15	70–80	120	Sripur	Jamuria	Tinpatia
PL24	Nimcha Harabanga PL	30	300	80	Satgram	Raniganj	Harabhanga
PL25	Real Kajora PL	20	>80	100	Kajora	Andal	Kajora
PL26	Chakrambati PL	15	80	90	Kajora	Andal	Railgate Majhipara

(continued)

Table 1 (continued)

Serial no.	Name of the PL	Origin of PL (years)	Area (bigha)	Depth (feet)	Area of mining	Block	Nearest village/town
PL27	Dhanderdihi 1 PL	50	<100	120	Kajora	Andal	Dhandadihi
PL28	Dhanderdihi 2 PL	12	50	80	Kajora	Andal	Dhandadihi
PL29	Dhandadihi 3 PL	30	50	100	Kajora	Andal	Dhandadihi
PL30	Porasiakhadan PL	20	>50	150	Kajora	Jamuria	Porasia
PL31	Babuisol Colony PL	30	125	30	Kajora	Andal	Palashban
PL32	Kumardihi PL	30	60	100	Bankola	Pandabeswar	Kumardihi
PL33	Kumardihi Old PL	35	200	300	Bankola	Pandabeswar	Kumardihi
PL34	Joyalbanga 2 PL	40	125–150	100	Bankola	Pandabeswar	Joyalbhanga
PL35	Sankarpur PL	10	< 90	70	Bankola	Andal	Sankarpur
PL36	Gunjan Ecological Park PL	40	250–300	80	Satgram	Jamuria	Sripur
PL37	Nimcha Damali Harabanga PL	29	250	80	Satgram	Raniganj	Damali
PL38	Patmohana Ranisayar PL	60	50	120	Sodepur	Kulti	Pathmohona
PL39	Vatas 2 PL	20	100	300	Sripur	Baraboni	Vatas
PL40	Chapuikhas PL	40	40	150	Satgram	Raniganj	Chanda

3 Characteristics of Pitlakes and Comparative Account of Different Pitlakes

As many as 40 PLs in RCF area were inventorized. Comparative studies of different PLs were done which are as described in Tables 2, 3, 4 and 5.

Table 2 The subdivision, block and Eastern Coalfields Limited (ECL) mining area wise location

Name of the PL	Subdivision	Block	ECL area of mining
Chora PL	Durgapur	Pandabeswar	Bankola
Joyalbhanga 1 PL	Durgapur	Pandabeswar	Bankola
Vatas 1 PL	Asansol	Baraboni	Sripur
Katapahari PL	Asansol	Baraboni	Sripur
Amdia PL	Asansol	Salanpur	Salanpur
Samdi PL	Asansol	Salanpur	Salanpur
Dalmia PL	Asansol	Salanpur	Salanpur
Bamna PL	Asansol	Salanpur	Salanpur
Bonbedi PL	Asansol	Salanpur	Salanpur
Alkusa Gopalpur PL	Asansol	Salanpur	Salanpur
Sikhdaspur PL	Asansol	Salanpur	Salanpur
Jambad 5 PL	Durgapur	Andal	Kajora
Jambad 4 PL	Durgapur	Andal	Kajora
Jambad Bottom-Up PL	Durgapur	Andal	Kajora
Western Kajora PL	Durgapur	Andal	Kajora
Atewal PL	Durgapur	Andal	Kajora
Khadan Kali PL	Durgapur	Andal	Kajora
Babuisol Sibmandir PL	Durgapur	Andal	Kajora
Ramnagar PL	Durgapur	Pandabeswar	Sodepur
Belpahari Kottadihi PL	Durgapur	Pandabeswar	Pandabeswar
Dalurbandh PL	Durgapur	Pandabeswar	Pandabeswar
Nagrakonda PL	Durgapur	Pandabeswar	Pandabeswar
Pathaldanga PL	Durgapur	Jamuria	Sripur
Nimcha Harabanga PL	Asansol	Raniganj	Satgram
Real Kajora PL	Durgapur	Andal	Kajora
Chakrambati PL	Durgapur	Andal	Kajora
Dhanderdihi 1 PL	Durgapur	Andal	Kajora
Dhanderdihi 2 PL	Durgapur	Andal	Kajora
Dhandadihi 3 PL	Durgapur	Andal	Kajora
Porasia Khadan PL	Asansol	Jamuria	Kajora
Babuisol Colony PL	Durgapur	Andal	Kajora
Kumardihi PL	Durgapur	Pandabeswar	Bankola
Kumardihi Old open-cast project (OCP) PL	Durgapur	Pandabeswar	Bankola
Joyalbanga 2 PL	Durgapur	Pandabeswar	Bankola
Sankarpur PL	Durgapur	Andal	Bankola
Gunjan Ecological Park PL	Asansol	Jamuria	Satgram
Nimcha Damali Harabanga PL	Asansol	Raniganj	Satgram
Patmohana Ranisayar PL	Asansol	Kulti	Sodepur
Vatas 2 PL	Asansol	Baraboni	Sripur
Chapuikhas PL	Asansol	Raniganj	Satgram

Table 3 A synoptic accounts of various PLs showing nearest village, age of PL, mean depth of PL and major uses of PL

Name of the PL	Nearest village/town	Age of PL (years)	Mean depth (feet)	Major uses
Chora PL	Chora	30	80	DOM
Joyalbhanga 1 PL	Joyalbhanga	35	70	DOM, LIB, IRR, WSP, RLG, PIS
Vatas 1 PL	Vatas	20	300	DOM, LIB, IRR, IDS, AGC
Katapahari PL	Katapahari	50	100	DOM, FSH, PIS
Amdia PL	Amdiha	40	250	DOM, FSH, WSP, RLG, PIS
Samdi PL	Samdi	20	250	DOM, LIB, WSP
Dalmia PL	Sikhdaspur	30	250	DOM, LIB, WSP
Bamna PL	Bodra	50	100	DOM, FSH, WSP, RLG, PIS
Bonbedi PL	Bonbedi	60	250	DOM, PIS
Alkusa Gopalpur PL	Alkusa	70	250	DOM, WSP, PIS
Sikhdaspur PL	Sikhdaspur	20	70	DOM, RLG, PIS
Jambad 5 PL	Benedi	70	150	DOM, LIB, PIS
Jambad 4 PL	Benedi	60	120	DOM, WSP
Jambad Bottom-Up PL	Benedi	50	100	DOM, LIB, IRR, FSH, PIS
Western Kajora PL	Kajora	40	40	DOM, RLG, PIS
Atewal PL	Jogrambati	40	60	DOM, PIS
Khadan Kali PL	Polashbon	40	40	DOM, RLG
Babuisol Sibmandir PL	Babuisol	15	60	DOM, RLG, PIS
Ramnagar PL	Ramnagar	10	400	WSP
Belpahari Kottadihi PL	Belpahari	10	40	DOM, PIS
Dalurbandh PL	Dalurbandh	40	100	DOM, LIB, RLG, PIS
Nagrakonda PL	Nagrakonda	3	100	DOM, LIB, FSH, PIS
Pathaldanga PL	Tinpatia	15	120	DOM, LIB, FSH, RLG
Nimcha Harabanga PL	Harabhanga	30	80	DOM, RLG, PIS
Real Kajora PL	Kajora	20	100	DOM, PIS
Chakrambati PL	Railgate Majhipara	15	90	DOM, LIB, FSH
Dhanderdihi 1 PL	Dhandadihi	50	120	DOM, FSH, RLG, PIS
Dhanderdihi 2 PL	Dhandadihi	12	80	DOM, IRR, PIS
Dhandadihi 3 PL	Dhandadihi	30	100	DOM, FSH
Porasia Khadan PL	Porasia	20	150	DOM, FSH, RLG, PIS
Babuisol Colony PL	Palashban	30	30	DOM, RLG
Kumardihi PL	Kumardihi	30	100	DOM, RLG, PIS
Kumardihi Old OCP PL	Kumardihi	35	300	DOM, PIS
Joyalbanga 2 PL	Joyalbhanga	40	100	DOM, FSH, PIS
Sankarpur PL	Sankarpur	10	70	DOM, IRR, RLG
Gunjan Ecological Park PL	Sripur	40	80	DOM
Nimcha Damali Harabanga PL	Damali	29	80	DOM, FSH, WSP, RLG, PIS
Patmohana Ranisayar PL	Pathmohona	60	120	DOM, LIB, PIS
Vatas 2 PL	Vatas	20	300	DOM, LIB, IRR, FSH, WSP, PIS
Chapuikhas PL	Chanda	40	150	DOM, LIB, FSH

DOM domestic use, *FSH* fishing purpose use, *WSP* water supply use, *RLG* religious purpose use, *PIS* pisciculture use, *LIB* livestock purpose use, *IRR* irrigation use

Table 4 The major problems of PL, cause of sinking, fishing activity and occurrence of migratory bird in these PLs

Name of the PL	Major problem	Cause of sinking	Fishing activity	Migratory bird
Chora PL	WDS	NIL	NIL	N
Joyalbhanga 1 PL	WTS,FIS	NIL	P	Y
Vatas 1 PL	WTS	ECR, FIL	PA	Y
Katapahari PL	WDS,WTS	ECR	P	Y
Amdia PL	WTS	ECR	P	Y
Samdi PL	NIL	FIL	P	N
Dalmia PL	FIS	NIL	P	Y
Bamna PL	WTS	ECR	P	N
Bonbedi PL	NIL	ECR	P	Y
Alkusa Gopalpur PL	WTS, FIS	NIL	P	Y
Sikhdaspur PL	WDS	NIL	P	Y
Jambad 5 PL	NIL	NIL	P	Y
Jambad 4 PL	WTS, FIS	NIL	P	Y
Jambad Bottom-Up PL	NIL	NIL	P, PA	Y
Western Kajora PL	FIS	NIL	P	Y
Atewal PL	FIS	NIL	P	N
Khadan Kali PL	FIS	NIL	P	Y
Babuisol Sibmandir PL	FIS	NIL	P	N
Ramnagar PL	WTS	ECR	NIL	N
Belpahari Kottadihi PL	NIL	NIL	PA	Y
Dalurbandh PL	WDS, FIS	NIL	P	Y
Nagrakonda PL	FIS	NIL	P	Y
Pathaldanga PL	NIL	ECR	P	N
Nimcha Harabanga PL	FIS	NIL	P	Y
Real Kajora PL	FIS	NIL	P	Y
Chakrambati PL	FIS	FIL	P	Y
Dhanderdihi 1 PL	FIS	NIL	P	Y
Dhanderdihi 2 PL	NIL	NIL	P	Y
Dhandadihi 3 PL	NIL	NIL	PA	N
Porasia Khadan PL	FIS	NIL	PA	N
Babuisol Colony PL	WDS	NIL	P	N
Kumardihi PL	FIS	NIL	P	N
Kumardihi Old OCP PL	NIL	IDS	P	Y
Joyalbanga 2 PL	FIS	NIL	P	N
Sankarpur PL	WTS	ECR, IDS	P	Y
Gunjan Ecological Park PL	NIL	NIL	P	Y
Nimcha Damali Harabanga PL	WTS	NIL	P	Y
Patmohana Ranisayar PL	NIL	NIL	P	N
Vatas 2 PL	NIL	ECR	P	Y
Chapuikhas PL	NIL	ECR	P	Y

WDS weed infestation, *WTS* water supply, *Fis* fishing activity, *ECR* encroachment, *FIL* filling, *IDS* industrial runoff, *P* present, *PA* past, *Y* yes, *N* no

Table 5 Classification of PL according to the subdivision, block, mining area, age, depth, fishing activity and abundance of migratory bird

Criteria of classification	Characteristic types	PL code	No. of PL	Percentage
Subdivision	Durgapur	PL01, PL02, PL12, PL13, PL14, PL15, PL16, PL17, PL18, PL19, PL20, PL21, PL22, PL23, PL25, PL26, PL27, PL28, PL29, PL31, PL32, PL33, PL34, PL35	24	60%
	Asansol	PL03, PL04, PL05, PL06, PL07, PL08, PL09, PL10, PL11, PL24, PL30, PL36, PL37, PL38, PL39, PL40	16	4%
Blocks	Pandabeswar	PL01, PL02, PL19, PL20, PL21, PL22, PL32, PL33, PL34	9	22.5%
	Baraboni	PL03, PL04, PL39	3	3.5%
	Salanpur	PL05, PL06, PL07, PL08, PL09, PL10, PL11	7	17.5%
	Andal	PL12, PL13, PL14, PL15, PL16, PL17, PL18, PL25, PL26, PL27, PL28, PL29, PL31, PL35	14	35%
	Jamuria	PL23, PL30, PL36	3	7.5%
	Raniganj	PL24, PL37, PL40	3	7.5%
	Kulti	PL38	1	2.5%
Area of mining	Bankola	PL01, PL02, PL32, PL33, PL34, PL35	6	15%
	Sripur	PL03, PL04, PL23, PL39	4	10%
	Salanpur	PL05, PL06, PL07, PL08, PL09, PL10, PL11	7	17.5%
	Kajora	PL12, PL13, PL14, PL15, PL16, PL17, PL18, PL25, PL26, PL27, PL28, PL29, PL30, PL31	14	35%
	Sodepur	PL19, PL38	2	5%
	Pandabeswar	PL20, PL21, PL22	3	7.5%
	Satgram	PL24, PL36, PL37, PL40	4	10%
Age	1–20 years	PL03, PL06, PL07, PL18, PL19, PL20, PL22, PL25, PL28, PL35, PL39	11	27.5%
	21–40 years	PL01, PL02, PL04, PL05, PL08, PL15, PL16, PL17, PL21, PL24, PL26, PL29, PL30, PL31, PL33, PL34, PL36, PL37, PL38, PL40	20	50%
	41–60 years	PL09, PL10, PL12, PL13, PL14, PL23, PL27, PL32	8	20%
	61–80 years	PL11	1	2.5%

(continued)

Table 5 (continued)

Criteria of classification	Characteristic types	PL code	No. of PL	Percentage
Depth	<100 ft	PL04, PL11, PL14, PL22, PL26, PL28, PL29, PL35, PL37, PL40	10	25%
	>100–<300 ft	PL01, PL02, PL03, PL05, PL06, PL08, PL09, PL10, PL12, PL13, PL15, PL16, PL17, PL18, PL20, PL21, PL24, PL25, PL27, PL30, PL31, PL32, PL33, PL34, PL36, PL38, PL39	27	67.5%
	>300 ft	PL07, PL19, PL23	3	7.5%
Fishing activity	Present	PL02, PL04, PL05, PL06, PL07, PL08, PL09, PL10, PL11, PL12, PL13, PL15, PL16, PL17, PL18, PL21, PL22, PL23, PL24, PL25, PL26, PL27, PL28, PL31, PL32, PL33, PL34, PL35, PL36, PL37, PL38, PL39, PL40	33	82.5%
	Past	PL03, PL20, PL29, PL30	4	10%
	Present and past	PL14	1	2.5%
	Nil	PL01, PL19	2	5%
Migratory birds	Present	PL02, PL03, PL04, PL05, PL07, PL09, PL10, PL11, PL12, PL13, PL14, PL15, PL17, PL20, PL21, PL22, PL24, PL25, PL26, PL27, PL28, PL33, PL35, PL36, PL37, PL39, PL40	27	67.5%
	Absent	PL01, PL06, PL08, PL16, PL18, PL19, PL23, PL29, PL30, PL31, PL32, PL34, PL38	13	32.5%

4 Physicochemical Characteristics of Pitlake Water

A consecutive 2-year study of physicochemical parameters of water was recorded at 27 selected mine PLs and presented in Table 6. A mean value of pH 7.72 was recorded which ranged between 6.93 and 9.01 during the study period. The mean values 442.87 μS/cm for conductivity and 294.75 mg/Lt for TDS were recorded in the present study. The highest value of alkalinity 41.33 mg/Lt was recorded along with the lowest value 16 mg/Lt along with mean value 26.72 mg/Lt. Total hardness value varied between 75.33 mg/Lt and 96.34 mg/Lt with a mean value of 223.70 mg/Lt. Chloride concentration ranged between 18.32 mg/Lt and 59.80 mg/Lt with a mean value of 32.42 mg/Lt. Among the nutrient parameters, nitrate nitrogen was recorded with a mean value of 17.17 mg/Lt which is much lower than the standard value. Similarly phosphate phosphorus was recorded with a mean value of 1.61 mg/Lt, respectively. The mean value of DO is 4.90 mg/Lt with a maximum value 6.68 mg/Lt and minimum 3.75 mg/Lt. BOD value ranged between 1.45 mg/Lt and 2.85 mg/Lt with a mean value of 2.20 mg/Lt.

Table 6 Variation of water parameters measured in PL with *National Standard (IS 10500)

Parameters	Code	Mean ± standard deviation	IS10500
pH	PH	7.72 ± 0.54	6.5–8.5
Conductivity (µS/cm)	CON	442.87 ± 210.95	–
TDS (mg/Lt)	TDS	294.75 ± 155.98	500
Alkalinity (mg/Lt)	ALK	26.72 ± 6.44	200
Hardness (mg/Lt)	HRD	223.70 ± 162.13	200
Chloride (mg/Lt)	CHL	32.42 ± 10.09	250
Nitrate nitrogen (mg/Lt)	NIN	17.17 ± 22.93	45
Phosphate phosphorus (mg/Lt)	PHO	1.61 ± 0.35	5
Dissolved oxygen	DO	4.90 ± 0.74	–
Biological oxygen demand	BOD	2.20 ± 0.31	3

Table 7 depicts the eigenvalues derived from discriminant analysis (DA) where F1 and F2 explain 73.79% of cumulative variations. A discriminant function analysis (Manly 1994; Legendre and Legendre 1998) was carried out to portray the differences in the water parameters and the PL as well. The data revealed significant variations among the PL in terms of the water physicochemical parameters, reflected through the discriminant function analysis (Fig. 1). Figure 2 revealed the distribution of PL in respect to its environmental condition.

The eigenvalue percentage of total variation explained by cumulative percentage of total variance and rotated loadings for daytime data, were given in Table 8. This table gives the relation of the factors with the water quality parameters. It was observed that the first factor explains the highest percentage of the entire variance. The subsequent factors have diminishing variance to explain the water quality. Although all factors having value >1 can be thought to be significant, this significance diminishes after the first three factors. The first eigenvalue was 2.61 and explains 26.12% of the total variation. The second was 1.76 and explains 17.62% of total variation, and the third was 1.24 and explains 12.44% of total variation. Figure 3 depicts the effect of water parameters on PL. Hardness, TDS and conductivity were three parameters that mostly affected the BOI, KUI, GEP, SIR, KOD, JOA and SAI PL. Phosphate phosphorus, alkalinity and chloride affected HI, JAD, CHA, WKA, DHI1, DO and BOD PL, and nitrate nitrogen were less significant in case of BKI, NHA, AGR, DAH, DAA and AMA PL. pH was significantly low in KHI, ATL, NDH, DHI3, DHI2, SAR, BSR, RKA and BCY PL.

5 Physicochemical Characteristics of Pitlake Soil

The descriptive analysis of physicochemical parameters of soil samples was represented in Table 9. A mean value of pH 7.29 was recorded during the study period. Conductivity was recorded with a mean value of 0.63 µS/cm. With a mean value of 1.69 g/cm^3, bulk density of soil varies from 0.31 to 13.87 g/cm^3. Particle density ranges from 0.61 to 31.49 g/cm^3 with a mean value of 6.01 g/cm^3. Water holding capacity ranges from 0.09 to 30.59 inch/ft. with a mean value of 8.39 inch/ft.

Table 7 Eigenvalues derived through discriminant analysis of water parameters during the study period

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Eigenvalue	9.3105	3.6783	1.4743	1.1272	0.5749	0.4928	0.4102	0.3180	0.1568	0.0581
Discrimination (%)	52.8966	20.8980	8.3763	6.4042	3.2664	2.8001	2.3306	1.8066	0.8909	0.3303
Cumulative (%)	52.8966	73.7946	82.1709	88.5751	91.8415	94.6416	96.9722	98.7788	99.6697	100.0000

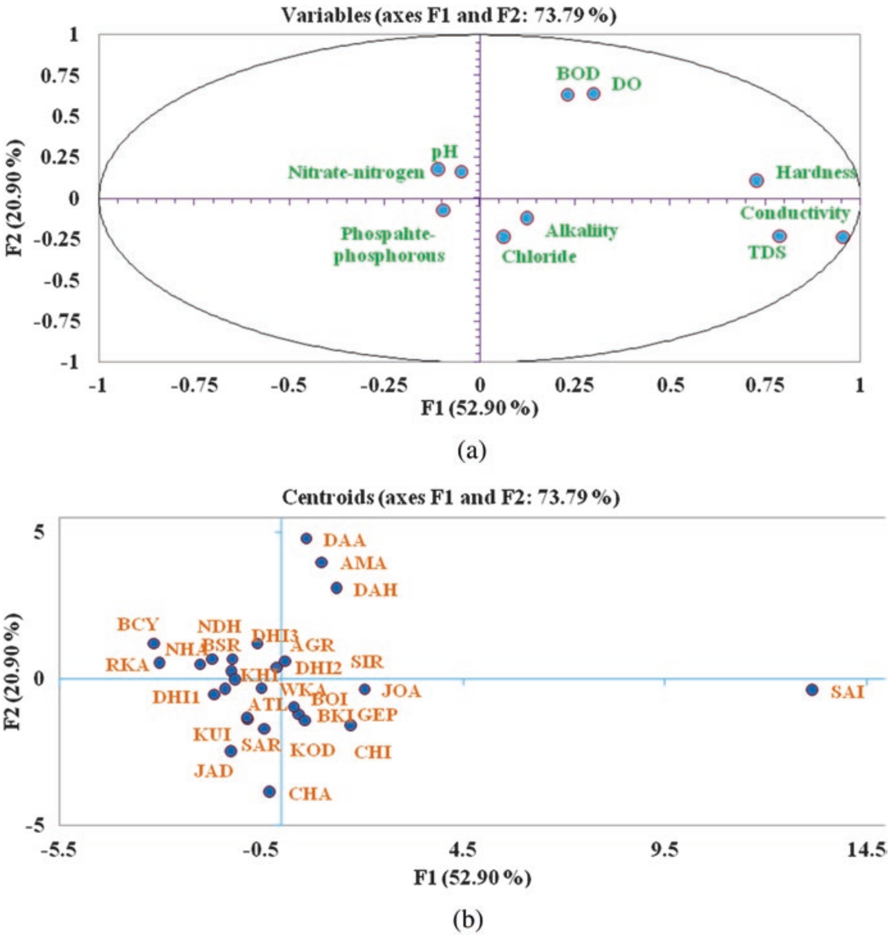


Fig. 1 The results of the discriminant analysis (DA) for the observed variations in the response variables (PL) against the explanatory variables (water parametric features). (**a**) Biplot with the ordination of the explanatory variables and (**b**) biplot with the ordination of the response variables

Organic carbon (OC) value ranges from 0.27 to 12.30 with a mean value of 3.32%. The mean values of available nitrogen (N) and phosphate phosphorus were observed with the mean values of 39.44 and 15.39 g/ha, respectively.

Table 10 depicts the eigenvalues derived from DA analysis where F1 and F2 explain 69.66% of cumulative variations. A discriminant function analysis (Manly 1994; Legendre and Legendre 1998) was carried out to portray the differences in the soil parameters and the PL as well. The data revealed significant variations among the PL in terms of the soil physicochemical parameters, reflected through the discriminant function analysis (Fig. 4). Figure 5 revealed the distribution of PL in respect with to its environmental condition.

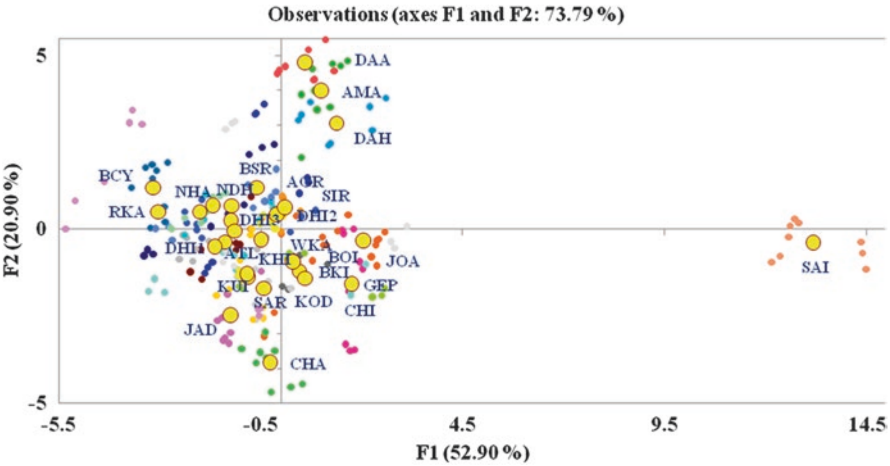


Fig. 2 Prevailing pattern of aquatic environment in RCF PL during the study period derived through DA of water parameters during the study period
CHA Chora, *JOA* Joyalbhanga, *AMA* Amdia, *SAI* Samdi, *DAA* Dalmia, *BOI* Bonbedi, *AGR* Alkusa Gopalpur, *SIR* Sikhdaspur, *JAD* Jambad, *WKA* Western Kajora, *ATL* Atewal, *KHI* Khadan Kali, *BSR* Babuisol Sibmandir, *BKI* Belpahari Kottadihi, *DAH* Dalurbandh, *NHA* Nimcha Harabhanga, *RKA* Real Kajora, *CHI* Chakrambati, *DHI1* Dhanderdihi 1, *DHI2* Dhanderdihi 2, *DHI3* Dhanderdihi 3, *BCY* Babuisol Colony, *KUI* Kumardihi, *KOD* Kumardihi Old, *SAR* Sankarpur, *GEP* Gunjan Ecological Park, *NDH* Nimcha Damali Harabhanga

The eigenvalues, percentage of total variation explained by cumulative percentage of total variance and rotated loadings for daytime data, were given in Table 11. This table gives the relation of the factors with the soil quality parameters. It was observed that the first factor explains the highest percentage of the entire variance. The subsequent factors have diminishing variance to explain the soil quality. Although all factors having value >1 can be thought to be significant, this significance diminishes after the first three factors. The first eigenvalue was 2.39 and explains 29.90% of the total variation, the second was 1.51 and explains 18.83% of total variation and the third was 1.14 and explains 14.22% of total variation.

6 Biological Resources of Pitlakes

6.1 Assessment of Plant Community

(a) *Hydrophyte Study*

Enumeration of Hydrophytes and Embarkment Plants in Pitlakes

PL hydrophytes and marginal floral assemblage observed during the study period is tabulated in Table 12. A total of 30 species belonging to 21 families of frequent hydrophytes and marginal plant species dominating these PLs were observed.

Table 8 Results of principal component analysis (PCA) showing eigenvectors of extracted components (>1), rotated using Varimax method with Kaiser normalization

Variable	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
pH	−0.1805	−0.3617	0.5612	0.1492	0.2286	−0.0607	0.4163	0.4830	−0.1596	0.1069
Conductivity	0.5264	−0.2136	0.0176	−0.0634	0.0576	−0.1373	−0.0480	−0.1027	−0.6850	−0.4107
TDS	0.5665	−0.1330	−0.0515	0.0092	0.0989	0.0404	0.0548	−0.0939	0.0071	0.7971
Alkalinity	0.0290	−0.0405	−0.3853	0.7230	−0.1173	−0.4965	0.2487	0.0089	0.0514	−0.0375
Hardness	0.5099	−0.2440	0.1623	0.0398	0.0809	0.0426	−0.0459	0.1274	0.6865	−0.3932
Chloride	0.1590	0.4501	−0.2820	−0.1983	0.3591	0.1735	0.6825	0.0855	0.0141	−0.1442
Nitrate nitrogen	−0.0606	0.2560	0.1865	0.2381	0.7960	−0.1892	−0.3516	−0.2146	0.0151	0.0047
Phosphate phosphorus	−0.1058	−0.3384	−0.2648	0.4114	0.1833	0.7596	−0.0333	−0.0914	−0.0982	−0.0720
DO	0.2368	0.5086	0.0628	0.2858	−0.1633	0.2120	−0.3209	0.6351	−0.1454	0.0250
BOD	0.1114	0.3214	0.5648	0.3199	−0.3025	0.1990	0.2527	−0.5158	−0.0095	−0.0434
Eigenvalue	2.6122	1.7622	1.2436	1.0784	1.0255	0.7915	0.5853	0.4344	0.2932	0.1736
Variability (%)	26.1219	17.6218	12.4364	10.7842	10.2551	7.9154	5.8534	4.3438	2.9322	1.7359
Cumulative (%)	26.1219	43.7437	56.1801	66.9643	77.2194	85.1347	90.9882	95.3320	98.2641	100.0000

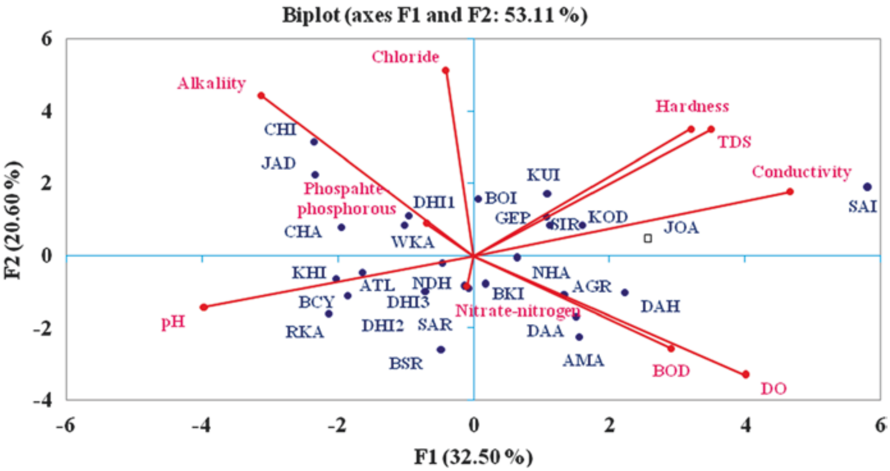


Fig. 3 Loading plots of PCA of water parameters for 27 PLs

Table 9 Descriptive statistics on soil parameters measured in PL during the study period

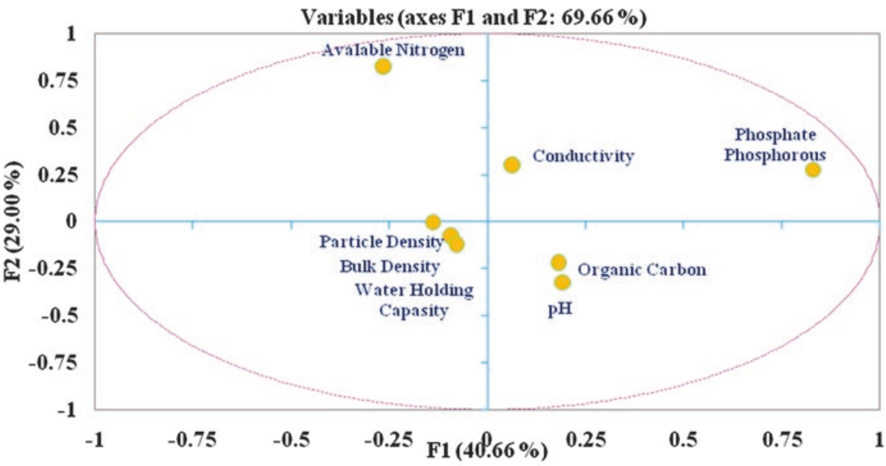
Soil parameter	Code	Mean
pH	PH	7.2859 ± 1.10
Conductivity (μS/cm)	CON	0.6337 ± 2.88
Bulk density (g/cm^3)	BDN	1.6929 ± 1.64
Particle density (g/cm^3)	PDN	6.0115 ± 5.81
Water holding capacity (inch/ft)	WHC	8.3899 ± 7.58
OC (%)	ORC	3.3243 ± 2.62
Available N (g/ha)	AVN	39.4387 ± 15.06
Available phosphate phosphorus (g/ha)	AVP	15.3944 ± 4.53

Table 10 Eigenvalues derived through DA of soil parameters during the study period

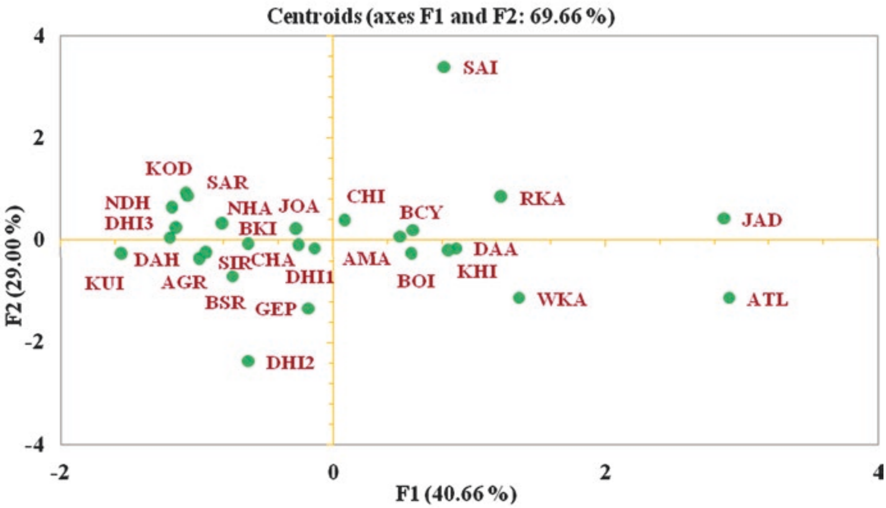
	F1	F2	F3	F4	F5	F6	F7	F8
Eigenvalue	1.6014	1.1422	0.5528	0.2587	0.1818	0.1158	0.0641	0.0220
Discrimination (%)	40.6577	28.9988	14.0353	6.5677	4.6145	2.9391	1.6282	0.5586
Cumulative (%)	40.6577	69.6565	83.6918	90.2595	94.8740	97.8131	99.4414	100.0000

Among these species eight were floating, four submerged and two reed swamp. Notable hydrophytes include *Hydrilla verticillata* (Indian star grass), *Nymphaea* sp. (water lily), *Salvinia* sp. (water moss), *Vallisneria spiralis* (eel grass), *Eichhornia crassipes* (water hyacinth), etc.

Variation in hydrophytes and embarkment plant type in PL of RCF is presented in Fig. 6. At 21 sites, of the total 30 plant species reported, 27% were represented by floating, 13% were represented by submerged, 7% were reed swamp and the rest of the 53% were represented by embankment/marginal plants.



(a)



(b)

Fig. 4 The results of the discriminant function analysis (DA) for the observed variations in the response variables (PL) against the explanatory variables (soil parametric features). (**a**) Biplot with the ordination of the explanatory variables and (**b**) biplot with the ordination of the response variables

(b) *Terrestrial Plant Study*

PL floral assemblage observed during the study period is tabulated in Tables 13, 14 and 15. A total of 56 species belonging to 29 families of frequent plant species dominating these PLs were observed. Among these species 34 were herbs, 7 shrubs and 15 trees. Fabaceae was the most dominant family comprising nine species each.

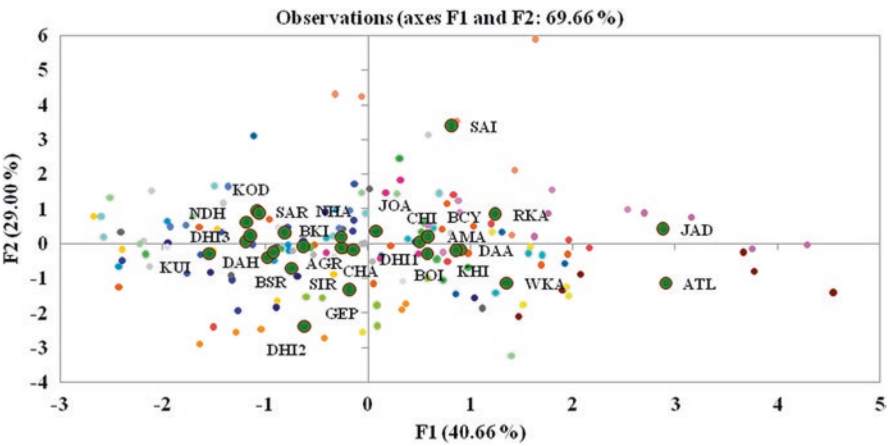


Fig. 5 Prevailing pattern of aquatic environment in RCF PL during the study period derived through DA of soil parameters during the study period

Table 11 Results of principal component analysis showing eigenvectors of extracted components (>1), rotated using Varimax method with Kaiser normalization

Variable	F1	F2	F3	F4	F5	F6	F7	F8
pH	0.1216	−0.5025	−0.0743	−0.6315	0.3968	0.3876	0.0727	−0.1235
Conductivity	−0.1010	0.0976	0.7718	−0.3970	0.1286	−0.4507	−0.0828	0.0194
OC	−0.5286	0.0619	−0.1024	−0.2039	−0.2165	−0.0731	0.7699	−0.1404
Bulk density	−0.1806	0.5777	0.1552	−0.2712	−0.2300	0.6450	−0.2419	−0.0924
Particle density	0.5367	0.2259	0.1012	−0.1058	−0.0369	0.1289	0.4550	0.6438
Water holding capacity	−0.4943	−0.3566	−0.0340	−0.0873	−0.2411	0.0636	−0.2734	0.6948
Available N	0.0183	−0.4131	0.5911	0.4566	−0.1815	0.4203	0.2103	−0.1315
Phosphate phosphorus	−0.3609	0.2267	0.0584	0.3180	0.7961	0.1671	0.1028	0.2039
Eigenvalue	2.3922	1.5062	1.1373	0.8963	0.7619	0.6256	0.3910	0.2896
Variability (%)	29.9029	18.8272	14.2161	11.2032	9.5237	7.8197	4.8877	3.6194
Cumulative (%)	29.9029	48.7301	62.9461	74.1493	83.6731	91.4928	96.3806	100.0000

The next important family is Asteraceae. Eighteen families were observed with only one species.

Variation in plant type around PL of RCF is shown in Fig. 7. At 27 sites, of the total 56 plant species reported, 61% were represented by herbs, 12% were represented by shrubs and 27% were represented by trees. Thus the study reveals that naturally occurring plant species at the site was dominated by herbs. Among all herbaceous species, *Lantana camara* (Raimunia), *Hyptis suaveolens* (American mint) and *Solanum sisymbriifolium* (sticky nightshade) are the most dominant species. It was noticed that *Calotropis gigantea* (crown flower) and *Saccharum*

Table 12 Enumeration of hydrophytes and embarkment plants in PL in RCF

Serial no.	Scientific name	Family	Habitat	PL01	PL02	PL04	PL05	PL06	PL07	PL09	PL11	PL13	PL15	PL16	PL17	PL20	PL21	PL24	PL31	PL32	PL33	PL34	PL36	PL37
1	*Chara* sp.	Characeae	Submerged	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	–	–
2	*Eichhornia crassipes*	Pontederiaceae	Floating	+	–	–	–	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–	+	–
3	*Enhydra fluctuans*	Asteraceae	Floating	–	–	–	–	+	+	–	–	+	–	–	+	–	–	–	–	–	–	–	–	–
4	*Hydrilla verticillata*	Hydrocharitaceae	Submerged	+	–	+	–	–	+	–	–	–	+	–	+	–	+	–	–	–	+	+	–	–
5	*Ipomoea aquatica*	Convolvulaceae	Floating	+	+	–	+	–	+	+	–	+	+	–	+	+	+	+	+	+	+	–	–	–
6	*Nymphaea* sp.	Nymphaeaceae	Floating	+	+	+	–	–	+	–	–	–	+	–	+	+	+	+	+	+	+	+	+	+
7	*Nymphaea nouchali*	Nymphaeaceae	Floating	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
8	*Nymphoides* sp.	Menyanthaceae	Floating	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	–	–	–	–	–	+
9	*Phragmites karka*	Poaceae	Reed swamp	–	–	–	–	–	–	–	–	–	+	–	–	–	+	–	+	–	–	–	–	–
10	*Potamogeton* sp.	Potamogetonaceae	Submerged	–	–	–	–	–	+	–	–	–	–	–	–	+	–	–	–	–	–	+	–	–
11	*Salvinia* sp.	Salviniaceae	Floating	–	–	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–
12	*Typha domingensis*	Typhaceae	Reed swamp	–	+	–	+	+	+	–	+	–	+	+	–	+	+	+	+	+	+	–	+	–
13	*Trapa natans*	Lythraceae	Floating	–	–	–	–	–	–	–	–	–	–	–	–	–	+	–	–	–	–	–	–	–
14	*Vallisneria spiralis*	Hydrocharitaceae	Submerged	–	–	–	–	–	–	–	–	–	–	+	–	–	–	–	–	–	–	+	–	–
15	*Achyranthes aspera*	Amaranthaceae	Embankment	–	+	–	+	–	+	–	–	+	+	–	–	+	+	–	–	–	+	+	–	–
16	*Alternanthera sessilis*	Amaranthaceae	Embankment	+	+	–	–	–	–	–	–	+	–	–	–	–	–	+	–	–	–	–	–	+
17	*Argemone mexicana*	Papaveraceae	Embankment	+	–	–	–	–	–	+	–	+	–	–	–	–	+	–	–	+	–	–	–	–
18	*Cassia sophera*	Fabaceae	Embankment	–	+	–	+	–	+	+	+	+	+	–	+	+	–	+	–	+	+	+	+	+
19	*Cassia tora*	Fabaceae	Embankment	–	+	–	+	+	+	+	+	+	+	–	+	–	–	+	+	+	+	–	–	+
20	*Centella asiatica*	Apiaceae	Embankment	–	–	–	–	–	–	–	–	+	–	–	–	+	–	–	–	–	–	–	–	–
21	*Cleome viscosa*	Capparidaceae	Embankment	+	+	–	+	–	–	+	–	+	+	–	–	–	+	–	–	+	+	–	+	–
22	*Hygrophila spinosa*	Acanthaceae	Embankment	–	–	–	–	–	–	–	–	+	+	+	–	–	–	–	–	–	–	–	–	–
23	*Ipomoea carnea*	Convolvulaceae	Embankment	+	+	+	+	+	+	+	+	+	+	–	+	+	+	+	+	+	–	+	–	+

24	*Lantana camera*	Verbenaceae	Embankment	+	+	–	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	–	–	+
25	*Lippia geminata*	Verbenaceae	Embankment	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
26	*Mikania* sp.	Asteraceae	Embankment	+	+	–	–	–	–	–	–	–	+	–	–	–	–	+	–	–	–	–	–	–
27	*Polygonum* sp.	Polygonaceae	Embankment	–	+	–	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–
28	*Saccharum spontaneum*	Poaceae	Embankment	+	–	+	–	+	–	–	–	–	–	+	–	+	+	–	–	+	–	+	–	–
29	*Sida cordifolia*	Malvaceae	Embankment	–	–	–	+	+	+	+	+	+	–	+	–	+	–	+	–	–	–	–	–	–
30	*Xanthium strumarium*	Asteraceae	Embankment	+	+	–	+	–	–	+	–	+	–	–	+	–	–	–	+	+	+	–	–	–

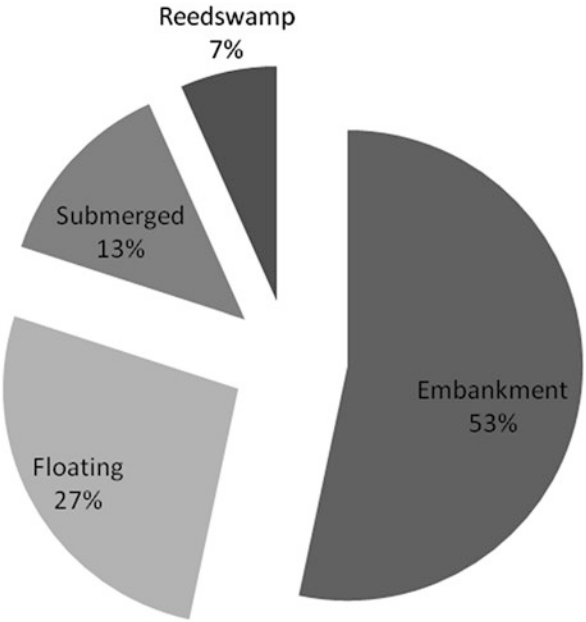


Fig. 6 Variation in hydrophytes and embarkment plant type in PL of RCF

spontaneum (Kans) are the most commonly occurring shrubs. It was also observed that *Acacia auriculiformis* (earleaf acacia) and *Azadirachta indica* (neem) were the most frequent naturally colonizing tree species around PL.

Table 16 depicts the abundance status of different plant species in PL which reveals that the highest percentage of plant frequency is found in Jambad 4 PL (34%) followed by Joyalbhanga 1 PL (29%), Amdia PL (28%), Chora PL (27%), Bonbedi PL (27%) and Alkusa Gopalpur PL (26%).

(c) *Successional Stages of Different Plant Community*

A hydrosere is a plant succession which occurs in an area of fresh water. In time, an area of open fresh water will naturally dry out, ultimately becoming woodland. During this change, a range of different land types such as swamp and marsh will succeed each other.

Phytoplankton Stage Unicellular floating algal plants such as diatoms are pioneer species of a bare waterbody, such as a pond. Their spores are carried by air to the pond. The phytoplankton is followed by zooplankton. They settle down to the bottom of the pond after death and decay into humus that mixes with silt and clay particles brought into the basin by runoff water and wave action and form soil. As soil builds up, the pond becomes shallower and further environmental changes follow.

Table 13 Enumeration of plants observed around PL of Pandabeswar and Jamuria block (RCF)

Serial no.	Plant name	Family	Type	Chora PL (PL01)	Joyalbanga PL01 (PL02)	Belpahari Kottadihi PL (PL20)	Dalurbandh PL (PL21)	Kumardihi PL (PL32)	Kumardihi Old OCP PL (PL33)	Sankarpur PL (PL35)	Gunjan Ecological Park PL (PL36)
1	*Acacia auriculiformis* Benth.	Fabaceae	Tree	–	+	+	+	+	+	+	+
2	*Acacia nilotica* (L.) Delile	Fabaceae	Tree	–	–	–	–	–	–	–	–
3	*Acalypha indica* L.	Euphorbiaceae	Herb	–	+	–	–	–	–	–	+
4	*Achyranthes aspera* L.	Amaranthaceae	Herb	–	+	+	+	+	+	–	–
5	*Aegle marmelos* (L.) Corrêa	Rutaceae	Tree	–	–	–	–	–	–	–	–
6	*Ailanthus excelsa* Roxb.	Simaroubaceae	Tree	–	–	+	–	–	–	–	–
7	*Albizia lebbeck* (L.) Benth.	Leguminosae	Tree	+	+	–	–	–	+	–	+
8	*Alstonia scholaris* (L.) R.Br.	Apocynaceae	Tree	–	–	–	–	–	–	–	–
9	*Amaranthus spinosus* L.	Amaranthaceae	Herb	+	+	–	–	–	–	–	–
10	*Amaranthus viridis* L.	Amaranthaceae	Herb	–	–	–	–	–	–	–	–
11	*Andrographis paniculata* (Burm. f.) Nees	Acanthaceae	Herb	–	–	–	–	–	–	–	–
12	*Argemone Mexicana* L.	Papaveraceae	Herb	+	+	–	+	+	–	–	–

(continued)

Table 13 (continued)

Serial no.	Plant name	Family	Type	Chora PL (PL01)	Joyalbanga PL01 (PL02)	Belpahari Kottadihi PL (PL20)	Dalurbandh PL (PL21)	Kumardihi PL (PL32)	Kumardihi Old OCP PL (PL33)	Sankarpur PL (PL35)	Gunjan Ecological Park PL (PL36)
13	*Azadirachta indica* A. Juss	Meliaceae	Tree	–	–	+	–	–	+	–	–
14	*Boerhavia diffusa* L.	Nyctaginaceae	Herb	–	–	–	–	–	+	–	–
15	*Borassus flabellifer* L.	Arecaceae	Tree	–	–	–	–	–	–	–	+
16	*Butea monosperma* (Lam.) Taub.	Fabaceae	Tree	–	–	–	–	+	–	–	+
17	*Caesalpinia pulcherrima* (L.) Sw.	Fabaceae	Tree	–	–	–	–	–	–	–	–
18	*Calotropis gigantea* (L.) W.T. Aiton	Asclepiadaceae	Shrub	+	+	+	+	+	+	+	+
19	*Cassia sophera* L.	Fabaceae	Herb	–	+	+	–	+	+	+	+
20	*Cassia tora* L.	Fabaceae	Herb	–	+	–	–	+	+	–	–
21	*Centella asiatica* (L.) Urb.	Apiaceae	Herb	–	–	–	–	–	–	–	–
22	*Cleome viscose* L.	Capparidaceae	Herb	+	+	+	+	+	+	+	+
23	*Clerodendrum viscosum* Vent.	Verbenaceae	Herb	+	+	–	+	+	–	+	–
24	*Colocasia esculenta* (L.) Schott	Araceae	Herb	+	–	–	–	–	+	+	+
25	*Commelina benghalensis* L.	Commelinaceae	Herb	+	+	+	+	+	+	+	+
26	*Croton bonplandianus* Baill.	Euphorbiaceae	Herb	+	+	+	+	+	+	+	+
27	*Dalbergia sissoo* Roxb.	Papilionaceae	Tree	+	–	–	–	–	+	–	+

28	*Desmodium gangeticum* (L.) DC.	Fabaceae	Herb	+	+	–	–	–	–	–	–
29	*Datura metel* L.	Solanaceae	Herb	+	–	–	–	+	+	+	+
30	*Eclipta alba* (L.) Hassk.	Asteraceae	Herb	–	+	–	–	–	–	–	–
31	*Eupatorium odoratum* L.	Asteraceae	Shrub	+	+	+	+	+	+	+	–
32	*Euphorbia hirta* L.	Euphorbiaceae	Herb	+	–	+	–	+	+	+	+
33	*Ficus benghalensis* L	Moraceae	Tree	+	+	–	–	–	–	–	–
34	*Ficus religiosa* L.	Moraceae	Tree	+	–	–	–	–	–	–	–
35	*Heliotropium indicum* L.	Boraginaceae	Herb	–	–	–	–	–	–	–	–
36	*Hyptis suaveolens* (L.) Poit.	Lamiaceae	Herb	+	+	+	+	+	+	+	–
37	*Ipomoea carnea* Jacq.	Convolvulaceae	Shrub	+	+	+	+	+	–	+	–
38	*Lantana camara* L.	Verbenaceae	Shrub	+	+	+	+	+	+	+	–
39	*Leonotis nepetifolia* (L.) R.Br.	Lamiaceae	Herb	–	–	–	–	–	–	+	–
40	*Leucas aspera* (Willd.) Link	Lamiaceae	Herb	+	+	+	+	+	+	+	+
41	*Mimosa pudica* L.	Fabaceae	Herb	–	–	–	–	–	–	–	–
42	*Oldenlandia corymbosa* L.	Rubiaceae	Herb	–	–	–	–	–	–	–	–
43	*Parthenium hysterophorus* L.	Compositae	Herb	+	+	+	+	+	+	+	+
44	*Pergularia daemia* (Forssk.) Chiov.	Asclepiadaceae	Herb	–	–	–	+	–	–	+	–

(continued)

Table 13 (continued)

Serial no.	Plant name	Family	Type	Chora PL (PL01)	Joyalbanga PL01 (PL02)	Belpahari Kottadihi PL (PL20)	Dalurbandh PL (PL21)	Kumardihi PL (PL32)	Kumardihi Old OCP PL (PL33)	Sankarpur PL (PL35)	Gunjan Ecological Park PL (PL36)
45	*Phoenix sylvestris* (L.) Roxb.	Arecaceae	Tree	+	–	+	–	–	+	+	–
46	*Phyllanthus amarus* Schumach. & Thonn.	Euphorbiaceae	Herb	–	+	–	–	–	–	–	+
47	*Saccharum spontaneum* L.	Poaceae	Herb	+	+	+	+	+	–	+	+
48	*Sida acuta* Burm.f.	Malvaceae	Herb	+	+	+	–	+	+	+	–
49	*Sida cordifolia* L.	Malvaceae	Herb	–	–	+	–	–	–	–	–
50	*Solanum sisymbriifolium* Lam.	Solanaceae	Herb	–	–	+	+	+	–	+	–
51	*Tephrosia purpurea* (L.) Pers.	Fabaceae	Herb	+	+	+	+	+	–	–	–
52	*Tridax procumbens* L.	Asteraceae	Herb	–	+	+	+	–	+	+	–
53	*Vernonia cinerea* (L.) Less.	Asteraceae	Shrub	+	–	–	–	+	+	–	–
54	*Vitex negundo* L.	Verbenaceae	Shrub	–	–	–	–	–	–	–	–
55	*Xanthium strumarium* L.	Asteraceae	Shrub	+	+	–	–	+	+	–	–
56	*Ziziphus jujuba* Mill.	Rhamnaceae	Tree	–	+	+	–	–	–	–	–

Table 14 Enumeration of plants observed around PL of Andal block (RCF)

Serial no.	Plant name	Family	Type	Jambad PL 4(PL13)	Western Kajora PL (PL15)	Atewal PL (PL16)	Khadan Kali PL (PL17)	Babuisol Shibmandir PL (PL18)	Real Kajora PL (PL25)	Chakrambati PL (PL26)	Dhanderdihi 1 PL (PL27)	Dhanderdihi 2 PL (PL28)	Dhandadihi 3 PL (PL29)	Babuisol Colony PL (PL31)
1	*Acacia auriculiformis* Benth.	Fabaceae	Tree	–	–	–	–	–	–	+	–	–	–	–
2	*Acacia nilotica* (L.) Delile	Fabaceae	Tree	–	–	+	–	–	–	–	–	–	–	+
3	*Acalypha indica* L.	Euphorbiaceae	Herb	–	–	–	–	–	–	–	–	–	–	–
4	*Achyranthes aspera* L.	Amaranthaceae	Herb	+	+	–	–	–	+	+	–	–	+	–
5	*Aegle marmelos* (L.) Corrêa	Rutaceae	Tree	+	+	–	–	–	–	–	–	–	–	–
6	*Ailanthus excelsa* Roxb.	Simaroubaceae	Tree	–	–	–	–	–	–	–	–	–	–	–
7	*Albizia lebbeck (L.)* Benth.	Leguminosae	Tree	–	–	–	–	–	–	–	+	–	–	–
8	*Alstonia scholaris* (L.) R.Br.	Apocynaceae	Tree	+	–	–	–	–	–	–	–	–	–	–
9	*Amaranthus spinous* L.	Amaranthaceae	Herb	+	+	–	+	+	–	–	–	–	–	+
10	*Amaranthus viridis* L.	Amaranthaceae	Herb	+	–	–	–	–	–	–	–	–	–	–
11	*Andrographis paniculata* (Burm.f.) Nees	Acanthaceae	Herb	–	–	–	–	–	–	–	–	–	+	–
12	*Argemone Mexicana* L.	Papaveraceae	Herb	+	+	+	+	–	+	+	–	+	–	–
13	*Azadirachta indica* A. Juss	Meliaceae	Tree	–	+	–	–	–	–	–	–	–	–	–
14	*Boerhavia diffusa* L.	Nyctaginaceae	Herb	+	–	–	+	–	–	+	–	–	–	–
15	*Borassus flabellifer* L.	Arecaceae	Tree	–	–	–	–	–	–	–	+	–	–	–
16	*Butea monosperma* (Lam.) Taub.	Fabaceae	Tree	+	+	–	+	+	–	–	+	+	–	–
17	*Caesalpinia pulcherrima* (L.) Sw.	Fabaceae	Tree	–	+	–	–	–	–	–	–	–	–	–

(continued)

Table 14 (continued)

Serial no.	Plant name	Family	Type	Jambad PL 4(PL13)	Western Kajora PL (PL15)	Atewal PL (PL16)	Khadan Kali PL (PL17)	Babuisol Shibmandir PL (PL18)	Real Kajora PL (PL25)	Chakrambati PL (PL26)	Dhanderdihi 1 PL (PL27)	Dhanderdihi 2 PL (PL28)	Dhandadihi 3 PL (PL29)	Babuisol Colony PL (PL31)
18	*Calotropis gigantean* (L.) W.T. Aiton	Asclepiadaceae	Shrub	+	+	+	+	+	+	+	+	+	+	+
19	*Cassia sopher*a L.	Fabaceae	Herb	+	+	–	+	+	+	+	–	–	–	–
20	*Cassia tora* L.	Fabaceae	Herb	+	+	–	+	+	+	+	–	–	–	+
21	*Centella asiatica* (L.) Urb.	Apiaceae	Herb	+	–	–	–	–	–	–	–	–	–	–
22	*Cleome viscose* L.	Capparidaceae	Herb	+	+	–	–	–	+	+	–	–	–	–
23	*Clerodendrum viscosum* Vent.	Verbenaceae	Herb	+	+	+	+	+	–	+	+	–	+	+
24	*Colocasia esculenta* (L.) Schott	Araceae	Herb	–	–	–	–	–	–	–	–	–	–	–
25	*Commelina benghalensis* L.	Commelinaceae	Herb	+	+	–	–	–	+	–	–	–	–	–
26	*Croton bonplandianus* Baill.	Euphorbiaceae	Herb	+	–	–	+	+	+	–	+	+	–	+
27	*Dalbergia sissoo* Roxb.	Papilionaceae	Tree	–	–	+	+	–	–	–	–	–	+	–
28	*Desmodium gangeticum* (L.) DC.	Fabaceae	Herb	+	–	–	–	–	–	–	–	–	–	–
29	*Datura metel* L.	Solanaceae	Herb	–	–	–	–	–	–	–	+	–	–	–
30	*Eclipta alba* (L.) Hassk.	Asteraceae	Herb	–	–	–	–	–	–	–	–	–	–	–
31	*Eupatorium odoratum* L.	Asteraceae	Shrub	+	+	+	+	+	+	+	+	+	+	+
32	*Euphorbia hirta* L.	Euphorbiaceae	Herb	+	+	–	+	+	–	–	–	–	–	+
33	*Ficus benghalensis* L	Moraceae	Tree	–	–	–	+	–	–	–	–	+	–	–
34	*Ficus religiosa L.*	Moraceae	Tree	–	–	–	–	–	–	–	–	+	–	–
35	*Heliotropium indicum* L.	Boraginaceae	Herb	–	–	–	–	+	–	–	–	–	–	–

36	*Hyptis suaveolens* (L.) Poit.	Lamiaceae	Herb	+	+	+	+	+	+	+	+	+	+	+
37	*Ipomoea carnea* Jacq.	Convolvulaceae	Shrub	+	+	–	+	+	–	+	+	+	–	+
38	*Lantana camara* L.	Verbenaceae	Shrub	+	+	+	+	+	+	+	+	+	+	+
39	*Leonotis nepetifolia* (L.) R.Br.	Lamiaceae	Herb	–	–	–	–	–	+	–	–	–	–	–
40	*Leucas aspera* (Willd.) Link	Lamiaceae	Herb	+	–	–	–	–	+	–	–	–	–	–
41	*Mimosa pudica* L.	Fabaceae	Herb	–	–	–	–	–	–	+	–	–	–	–
42	*Oldenlandia corymbosa* L.	Rubiaceae	Herb	+	–	–	–	–	+	–	–	–	–	–
43	*Parthenium hysterophorus* L.	Compositae	Herb	+	+	+	+	+	+	+	+	+	+	+
44	*Pergularia daemia* (Forssk.) Chiov.	Asclepiadaceae	Herb	–	–	–	+	–	–	–	–	–	–	–
45	*Phoenix sylvestris* (L.) Roxb.	Arecaceae	Tree	–	+	+	+	+	–	+	+	+	+	+
46	*Phyllanthus amarus* Schumach. & Thonn.	Euphorbiaceae	Herb	+	–	–	–	–	+	–	–	–	–	–
47	*Saccharum spontaneum* L.	Poaceae	Herb	+	–	+	–	+	+	+	+	+	–	+
48	*Sida acuta* Burm.f.	Malvaceae	Herb	+	+	+	+	+	+	+	–	–	–	+
49	*Sida cordifolia* L.	Malvaceae	Herb	+	–	+	–	+	+	+	+	–	+	–
50	*Solanum sisymbriifolium* Lam.	Solanaceae	Herb	+	–	–	–	+	–	+	–	–	–	–
51	*Tephrosia purpurea* (L.) Pers.	Fabaceae	Herb	+	+	+	–	+	–	–	+	+	+	–
52	*Tridax procumbens* L.	Asteraceae	Herb	–	–	+	+	+	+	–	–	+	+	–
53	*Vernonia cinerea* (L.) Less.	Asteraceae	Shrub	+	–	–	–	–	+	–	–	–	–	+
54	*Vitex negundo* L.	Verbenaceae	Shrub	–	–	–	–	–	–	+	+	–	–	–
55	*Xanthium strumarium* L.	Asteraceae	Shrub	+	–	+	+	–	+	+	–	–	–	+
56	*Ziziphus jujuba* Mill.	Rhamnaceae	Tree	+	+	+	+	+	+	+	+	–	+	+

Table 15 Enumeration of plants observed around PL of Salanpur and Raniganj block (RCF)

Serial no.	Plant name	Family	Type	Amdia PL (PL05)	Samdi PL (PL06)	Dalmia PL (PL07)	Bonbedi PL (PL09)	Alkusa Gopalpur PL (PL10)	Sikhdaspur PL (PL11)	Nimcha Harabanga PL (PL24)	Nimcha Damali Harabanga PL (PL37)
1	*Acacia auriculiformis* Benth.	Fabaceae	Tree	+	+	+	–	+	–	–	–
2	*Acacia nilotica* (L.) Delile	Fabaceae	Tree	–	–	–	–	–	–	–	–
3	*Acalypha indica* L.	Euphorbiaceae	Herb	–	–	–	–	–	–	–	–
4	*Achyranthes aspera* L.	Amaranthaceae	Herb	+	–	+	+	+	–	–	–
5	*Aegle marmelos* (L.) Corrêa	Rutaceae	Tree	–	–	–	–	–	–	–	–
6	*Ailanthus excelsa* Roxb.	Simaroubaceae	Tree	+	–	–	–	–	+	+	+
7	*Albizia lebbeck* (L.) Benth.	Leguminosae	Tree	–	–	–	–	+	–	+	–
8	*Alstonia scholaris* (L.) R.Br.	Apocynaceae	Tree	–	–	–	–	–	–	–	–
9	*Amaranthus spinous* L.	Amaranthaceae	Herb	–	–	–	+	–	–	–	–
10	*Amaranthus viridis* L.	Amaranthaceae	Herb	–	–	–	–	–	–	–	–
11	*Andrographis paniculata* (Burm.f.) Nees	Acanthaceae	Herb	–	–	–	–	–	–	–	–
12	*Argemone Mexicana* L.	Papaveraceae	Herb	–	–	–	+	+	–	–	–
13	*Azadirachta indica* A. Juss	Meliaceae	Tree	+	+	–	+	+	+	–	–
14	*Boerhavia diffusa* L.	Nyctaginaceae	Herb	–	–	+	–	+	–	–	–
15	*Borassus flabellifer* L.	Arecaceae	Tree	–	–	–	–	–	+	–	–
16	*Butea monosperma* (Lam.) Taub.	Fabaceae	Tree	+	–	+	+	–	+	+	+
17	*Caesalpinia pulcherrima* (L.) Sw.	Fabaceae	Tree	–	–	–	–	–	–	–	–
18	*Calotropis gigantean* (L.) W.T. Aiton	Asclepiadaceae	Shrub	–	+	+	+	+	–	+	+
19	*Cassia sophera* L.	Fabaceae	Herb	+	–	+	+	–	+	+	+
20	*Cassia tora* L.	Fabaceae	Herb	+	+	+	+	+	+	+	+
21	*Centella asiatica* (L.) Urb.	Apiaceae	Herb	–	–	–	–	–	–	–	–
22	*Cleome viscose* L.	Capparidaceae	Herb	+	–	–	+	+	–	–	–

23	*Clerodendrum viscosum* Vent.	Verbenaceae	Herb	–	+	+	+	+	+	+	–
24	*Colocasia esculenta* (L.) Schott	Araceae	Herb	–	–	–	–	–	–	–	–
25	*Commelina benghalensis* L.	Commelinaceae	Herb	+	+	–	–	–	–	–	–
26	*Croton bonplandianus* Baill.	Euphorbiaceae	Herb	+	+	+	+	+	+	+	+
27	*Dalbergia sissoo* Roxb.	Papilionaceae	Tree	–	–	–	–	–	–	–	–
28	*Desmodium gangeticum* (L.) DC.	Fabaceae	Herb	–	–	–	–	–	–	–	–
29	*Datura metel* L.	Solanaceae	Herb	+	–	–	+	–	–	+	–
30	*Eclipta alba* (L.) Hassk.	Asteraceae	Herb	–	+	–	–	–	–	–	–
31	*Eupatorium odoratum* L.	Asteraceae	Shrub	+	+	–	+	+	+	+	+
32	*Euphorbia hirta* L.	Euphorbiaceae	Herb	+	+	–	+	+	+	+	+
33	*Ficus benghalensis* L.	Moraceae	Tree	–	+	–	–	–	–	–	–
34	*Ficus religiosa L.*	Moraceae	Tree	–	–	–	+	–	–	–	–
35	*Heliotropium indicum* L.	Boraginaceae	Herb	–	–	–	–	–	–	–	–
36	*Hyptis suaveolens* (L.) Poit.	Lamiaceae	Herb	+	+	–	+	+	+	+	+
37	*Ipomoea carnea* Jacq.	Convolvulaceae	Shrub	+	+	+	+	+	+	+	+
38	*Lantana camara* L.	Verbenaceae	Shrub	+	+	+	+	+	+	+	+
39	*Leonotis nepetifolia* (L.) R.Br.	Lamiaceae	Herb	+	–	+	+	–	–	–	–
40	*Leucas aspera* (Willd.) Link	Lamiaceae	Herb	–	–	–	–	–	+	+	–
41	*Mimosa pudica* L.	Fabaceae	Herb	–	–	–	–	+	–	+	–
42	*Oldenlandia corymbosa* L.	Rubiaceae	Herb	–	–	–	+	+	–	–	–
43	*Parthenium hysterophorus* L.	Compositae	Herb	+	+	+	+	+	+	+	+
44	*Pergularia daemia* (Forssk.) Chiov.	Asclepiadaceae	Herb	+	–	–	–	–	–	–	+
45	*Phoenix sylvestris* (L.) Roxb.	Arecaceae	Tree	+	–	+	–	+	+	+	+
46	*Phyllanthus amarus* Schumach. & Thonn.	Euphorbiaceae	Herb	–	–	–	–	–	–	–	–
47	*Saccharum spontaneum* L.	Poaceae	Herb	+	+	+	+	+	+	+	+

(continued)

Table 15 (continued)

Serial no.	Plant name	Family	Type	Amdia PL (PL05)	Samdi PL (PL06)	Dalmia PL (PL07)	Bonbedi PL (PL09)	Alkusa Gopalpur PL (PL10)	Sikhdaspur PL (PL11)	Nimcha Harabanga PL (PL24)	Nimcha Damali Harabanga PL (PL37)
48	*Sida acuta* Burm.f.	Malvaceae	Herb	+	–	–	+	+	+	+	+
49	*Sida cordifolia* L.	Malvaceae	Herb	+	+	+	+	+	+	+	–
50	*Solanum sisymbriifolium* Lam.	Solanaceae	Herb	+	+	+	–	+	+	–	–
51	*Tephrosia purpurea* (L.) Pers.	Fabaceae	Herb	+	+	–	–	–	+	–	+
52	*Tridax procumbens* L.	Asteraceae	Herb	+	+	–	+	+	–	–	–
53	*Vernonia cinerea* (L.) Less.	Asteraceae	Shrub	–	–	–	–	–	–	–	–
54	*Vitex negundo* L.	Verbenaceae	Shrub	–	–	–	–	–	–	–	–
55	*Xanthium strumarium* L.	Asteraceae	Shrub	+	–	–	+	–	+	+	–
56	*Ziziphus jujuba* Mill.	Rhamnaceae	Tree	+	+	–	+	+	+	+	+

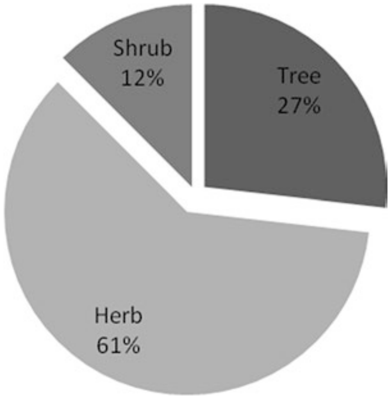


Fig. 7 Variation in plant type around PL of RCF

Submerged Stage As the waterbody becomes shallower, more submerged rooted species are able to become established due to increasing light penetration in the shallower water. This is suitable for growth of rooted submerged species such as *Myriophyllum*, *Vallisneria*, *Elodea*, *Hydrilla* and *Ceratophyllum*. These plants root themselves in mud. Once submerged species colonize, the successional changes are more rapid and are mainly autogenic as organic matter accumulates. Inorganic sediment is still entering the lake and is trapped more quickly by the net of plant roots and rhizomes growing on the pond floor. The pond becomes sufficiently shallow (2–5 ft) for floating species and less suitable for rooted submerged plants.

Floating Stage The floating plants are rooted in the mud, but some or all their leaves float on the surface of the water. These include species like *Nymphaea*, *Nelumbo* and *Potamogeton*. Some free-floating species also become associated with root plants. The large and broad leaves of floating plants shade the water surface, and conditions become unsuitable for growth of submerged species which start disappearing. The plants decay to form organic mud which makes the pond shallower yet (1–3 ft).

Reed Swamp Stage The pond is now invaded by emergent plants such as *Phragmites* (reed grasses), *Typha* (cattail) and *Zizania* (wild rice) to form a reed swamp. These plants have creeping rhizomes which knit the mud together to produce large quantities of leaf litter. This litter is resistant to decay, and reed peat builds up, accelerating the autogenic change. The surface of the pond is converted into water-saturated marshy land.

Sedge Meadow Stage Successive decreases in the water level and changes in substratum help members of Cyperaceae and Gramineae such as *Carex* spp. and *Juncus* to establish them. They form a mat of vegetation extending towards the centre of the pond. Their rhizomes knit the soil further. The above water leaves transpire water to lower the water level further and add additional leaf litter to the soil. Eventually the sedge peat accumulates above the water level, and soil is no longer totally water-

Table 16 Abundance of plant species observed around PL in studied PL of RCF

Sites	Status	Frequency	Relative frequency
Chora PL	0	29	51.79
	1	27	48.21
Joyalbhanga 1 PL	0	27	48.21
	1	29	51.79
Amdia PL	0	28	50.00
	1	28	50.00
Samdi PL	0	35	62.50
	1	21	37.50
Dalmia PL	0	39	69.64
	1	17	30.36
Bonbedi PL	0	29	51.79
	1	27	48.21
Alkusa Gopalpur PL	0	30	53.57
	1	26	46.43
Sikhdaspur PL	0	33	58.93
	1	23	41.07
Jambad 4 PL	0	22	39.29
	1	34	60.71
Western Kajora PL	0	33	58.93
	1	23	41.07
Atewal PL	0	39	69.64
	1	17	30.36
Khadan Kali PL	0	33	58.93
	1	23	41.07
Babuisol Sibmandir PL	0	34	60.71
	1	22	39.29
Belpahari Kottadihi PL	0	32	57.14
	1	24	42.86
Dalurbandh PL	0	37	66.07
	1	19	33.93
Nimcha Harabanga PL	0	33	58.93
	1	23	41.07
Real Kajora PL	0	33	58.93
	1	23	41.07
Chakrambati PL	0	33	58.93
	1	23	41.07
Dhanderdihi 1 PL	0	38	67.86
	1	18	32.14
Dhanderdihi 2 PL	0	41	73.21
	1	15	26.79
Dhandadihi 3 PL	0	42	75.00
	1	14	25.00
Babuisol Colony PL	0	38	67.86
	1	18	32.14

(continued)

Table 16 (continued)

Sites	Status	Frequency	Relative frequency
Kumardihi PL	0	31	55.36
	1	25	44.64
Kumardihi Old OCP PL	0	31	55.36
	1	25	44.64
Sankarpur PL	0	33	58.93
	1	23	41.07
Gunjan Ecological Park PL	0	38	67.86
	1	18	32.14
Nimcha Damali Harabanga PL	0	38	67.86
	1	18	32.14

1 = total number of species present, 0 = total number of species absent

Table 17 Successional stages of PL in RCF areas

Phytoplankton stage	Submerged stage	Floating stage	Reed swamp stage	Sedge meadow stage	Woodland stage	Climax stage
	PL01, PL04, PL07, PL15, PL16, PL17, PL20, PL21, PL33, PL34	PL01, PL02, PL04, PL05, PL06, PL07, PL09, PL11, PL13, PL15, PL17, PL20, PL21, PL24, PL31, PL32, PL33, PL34, PL36, PL37	PL02, PL05, PL06, PL07, PL11, PL15, PL16, PL20, PL21, PL24, PL31, PL32, PL33, PL36			

logged. The habitat becomes suitable for invasion of herbs (secondary species) such as *Mentha*, *Caltha*, *Iris* and *Galium* which grow luxuriantly and bring further changes to the environment. Mesic conditions develop and marshy vegetation begins to disappear.

Woodland Stage The soil now remains drier for most of the year and becomes suitable for development of wet woodland. It is invaded by shrubs and trees such as *Salix* (willow), *Alnus* (alder) and *Populus* (poplar). These plants react upon the habitat by producing shade, lower the water table still further by transpiration, build up the soil and lead to the accumulation of humus with associated microorganisms.

Climax Stage Finally a self-perpetuating climax community develops. It may be a forest if the climate is humid, a grassland in case of subhumid environment or a desert in arid and semiarid conditions. A forest is characterized by the presence of all types of vegetation including herbs, shrubs, mosses, shade-loving plants and trees. Decomposers are frequent in climax vegetation.

Successional stages of all PLs were noticed (Table 17), and it was found that phytoplankton stage was absent in case of all PLs. Submerged stages are predominant in PL, i.e., Chora (PL 01), Katapahari (PL 04), Dalmia (PL 07), Western Kajora

(PL 15), Atewal (PL 16), Khadan Kali (PL 17), Belpahari Kottadihi (PL 20), Dalurbandh (PL 21), Kumardihi Old (PL 33) and Joalbhanga 2 (PL 34). All PL vegetation showed floating stages of successional pattern except Atewal (PL 16). Reed swamp stage of vegetation structure was also noticed in almost all PLs except Chora (PL 01), Katapahari (PL 04), Bonbedi (PL 09), Jambad 4 (PL 13), Khadan Kali (PL 17), Joalbhanga 2 (PL 34) and Nimcha Damali Harabhanga (PL 37). Sedge meadow stage, woodland stage and climax stage were absent in all studied PLs in RCF areas.

Categorization of Pitlakes on the Basis of Successional Characteristics
Successional stages of 21 PLs in RCF areas are given in Table 17. On the basis of successional stages, the PL can be put into three categories; a brief account on each of which is presented in the following:

(i) Waterbodies rich in rooted submerged hydrophytes like Indian star grass, eel grass, etc. which grow at various depths and seen in PL01 (Chora PL), PL04 (Katapahari PL), PL06 (Samdi PL), PL07 (Dalmia PL), PL15 (Western Kajora), PL16 (Atewal PL), PL17 (Kadhan kali), PL20 (Belpahari Kottadihi PL), PL21 (Dalurbandh PL), PL33 (Kumardihi Old OCP PL) and PL34 (Joyalbhanga 2 PL).

(ii) Waterbodies dominated by plant species rooted in the mud with their leaves reaching the water surface to float, e.g., *Nymphaea nouchali* (blue water lily), *Trapa natans* (water chestnut), etc., and by free-floating plants that are not fixed in the mud, e.g., *Lemna* sp. (duckweed), water moss, etc., as seen in PL01 (Chora PL), PL02 (Joyalbanga PL1), PL04 (Katapahari PL), PL05 (Amdia PL), PL07 (Dalmia PL), PL09 (Bonbedi PL), PL11 (Sikhdaspur PL), PL13 (Jambad 4 PL), PL15 (Western Kajora PL), PL17 (Khadan Kali PL), PL20 (Belpahari Kottadihi PL), PL21 (Dalurbandh PL), PL24 (Nimcha Harabanga PL), PL31 (Babuisol Colony PL), PL32 (Kumrdihi PL), PL33 (Kumardihi Old OCP PL), PL34 (Joyalbhanga 2 PL), PL36 (Gunjon Ecological Park PL) and PL37 (Nimcha Harabanga Damali PL).

(iii) Waterbodies in reed swamp stage with plants that are mostly rooted, but most parts of their shoots remain exposed, e.g., amphibious plants like *Typha domingensis* (cattail), etc. These plants react not only to shade the surface water but also to build up the margins by retaining sedimentary material washed into the waterbody and rapidly accumulating plant remains. These plant populations are much denser. PLs that belong to this category are PL02 (Joyalbanga 1 PL), PL05 (Amdia PL), PL06 (Samdi PL), PL07 (Dalmia PL), PL11 (Sikhdaspur PL), PL15 (Western Kajora PL), PL16 (Atewal PL), PL20 (Belpahari Kottadihi PL), PL21 (Dalurbandh PL), PL24 (Nimcha Harabanga PL), PL31 (Babuisol Colony PL), PL32 (Kumrdihi PL), PL33 (Kumardihi old OCP PL) and PL36 (Gunjon Ecological Park PL).

6.2 Enumeration of Avifaunal Composition in and Around Pitlakes of RCF

(a) *Residential Avifaunal Composition in Pitlakes During the Study Period*

Good and effective aquatic life supporting environment have been observed in these PLs which is also supported by the rich avifaunal resources in and around these PLs. Fifty nine species of wetland birds (with terrestrial counterparts in the adjoining floral habitat) belonging to 15 orders and 34 families were recorded (Table 18). The family Passeriformes represented by 22 species dominated the wetland bird community of the study area. Lesser whistling duck (*Dendrocygna javanica*) is the most important resident bird in these PLs.

6.3 Notable Piscifauna Observed in Pitlakes

During the study period, the 15 most frequently cultured/naturally occurred fish species under 4 orders, 5 families and 14 genera were collected and identified from the PL of RCF, West Bengal, India (Table 19). The maximum number of species was found under the order Cypriniformes (11). Cyprinidae was the most species (11)-bearing family. Our study revealed that according to the red list threat category, least concern (LC) category (66.66%) was the maximum fish species-comprising category followed by not evaluated (NE, 11%), near threatened (NT, 20%) and data deficient (6.66%), respectively. The population trend includes 73.33% fish species with unknown status (UN) followed by 20% with decreasing (DE) and only 6.66% fishes with stable (ST) status. We found that there is ample scope of intensive pisciculture practices in most of the PL.

Developmental Project Based on Pitlake Water for Site-Specific Pisciculture Practices

Pitlakes are large deep open ecosystem. We have inventorized 40 PLs, and among them recreational fishing and for feeding purposes fishing activity take place in 34 PLs. Sometimes commercial fishing takes place for some 18 PLs as secondary livelihood purposes. After analysis of PL water quality and questionnaire survey of local stakeholder, we have recorded that developmental pisciculture project can be started in 25 PLs. These PLs are, namely, Joyalbhanga 1 PL, Vatas 1 PL, Amdia PL, Samdi PL, Dalmia PL, Bamna PL, Bonbedi PL, Alkusa Gopalpur PL, Sikhdaspur PL, Jambad 5 PL, Jambad 4 PL, Jambad bottom-up PL, Atewal PL, Khadan Kali PL, Dalurbandh PL, Nagrakonda PL, Pathaldanga PL, Nimcha Harabanga PL, Real Kajora PL, Dhandadihi 2 PL, Babuisol Colony PL, Kumardihi Old OCP PL, Joyalbhanga 2 PL, Nimcha Damali Harabanga PL and Vatas 2 PL. The abovementioned PLs were selected in accordance with their suitability for aquaculture practice. Due to high adaptability of such PL, the pisciculture techniques will be initiated here.

Table 18 Enumeration of residential birds observed in and around PL of RCF

Species code	Bird name	Scientific name	Order	Family	Population trend	Status
S1	Ashy prinia	*Prinia socialis*	Passeriformes	Cisticolidae	Stable	R
S2	Ashy wood swallow	*Artamus fuscus*	Passeriformes	Artamidae	Stable	R
S3	Asian openbill stork	*Anastomus oscitans*	Ciconiiformes	Ciconiidae	Unknown	R
S4	Asian palm swift	*Cypsiurus balasiensis*	Caprimulgiformes	Apodidae	Stable	R
S5	Asian pied starling	*Sturnus contra*	Passeriformes	Sturnidae	Increasing	R
S7	Bengal bush lark	*Mirafra assamica*	Passeriformes	Alaudidae	Stable	R
S8	Black-crowned night heron	*Nycticorax nycticorax*	Pelecaniformes	Ardeidae	Decreasing	R
S9	Black drongo	*Dicrurus macrocercus*	Passeriformes	Dicruridae	Unknown	R
S10	Black-hooded oriole	*Oriolus xanthornus*	Passeriformes	Oriolidae	Unknown	R
S11	Black kite	*Milvus migrans*	Accipitriformes	Accipitridae	Unknown	R
S12	Black-rumped flameback	*Dinopium benghalense*	Piciformes	Picidae	Stable	R
S14	Brahminy kite	*Haliastur indus*	Accipitriformes	Accipitridae	Decreasing	R
S15	Brahminy sterling	*Sturnus pagodarum*	Passeriformes	Sturnidae	Unknown	R
S16	Bronze-winged jacana	*Metopidius indicus*	Charadriiformes	Jacanidae	Unknown	R
S18	Cattle egret	*Bubulcus ibis*	Pelecaniformes	Ardeidae	Increasing	R
S19	Chestnut-tailed starling	*Sturnus malabaricus*	Passeriformes	Sturnidae	Unknown	R
S21	Common kingfisher	*Alcedo atthis*	Coraciiformes	Alcedinidae	Unknown	R
S22	Common moorhen	*Gallinula chloropus*	Gruiformes	Rallidae	Stable	R
S23	Common myna	*Acridotheres tristis*	Passeriformes	Sturnidae	Increasing	R
S26	Common tailorbird	*Orthotomus sutorius*	Passeriformes	Sylviidae	Stable	R
S27	Coppersmith barbet	*Psilopogon haemacephalus*	Piciformes	Megalaimidae	Increasing	R
S31	Greater coucal	*Centropus sinensis*	Cuculiformes	Cuculidae	Stable	R
S32	Green bee eater	*Merops orientalis*	Coraciiformes	Meropidae	Increasing	R
S34	House crow	*Corvus splendens*	Passeriformes	Corvidae	Stable	R
S35	House sparrow	*Passer domesticus*	Passeriformes	Passeridae	Decreasing	R
S36	Indian cormorant	*Phalacrocorax fuscicollis*	Suliformes	Phalacro coracidae	Unknown	R
S37	Indian pond heron	*Ardeola grayii*	Pelecaniformes	Ardeidae	Unknown	R

S38	Indian robin	*Saxicoloides fulicatus*	Passeriformes	Muscicapidae	Stable	R
S39	Indian silverbill	*Lonchura malabarica*	Passeriformes	Estrildidae	Stable	R
S40	Jungle babbler	*Turdoides striata*	Passeriformes	Timaliidae	Stable	R
S41	Lesser whistling duck	*Dendrocygna javanica*	Anseriformes	Anatidae	Decreasing	R
S42	Little egret	*Egretta garzetta*	Pelecaniformes	Ardeidae	Increasing	R
S43	Oriental magpie robin	*Copsychus saularis*	Passeriformes	Muscicapidae	Stable	R
S45	Purple sunbird	*Nectarinia asiatica*	Passeriformes	Nectariniidae	Stable	R
S46	Red-vented bulbul	*Pycnonotus cafer*	Passeriformes	Pycnonotidae	Increasing	R
S48	Red-whiskered bulbul	*Pycnonotus jocosus*	Passeriformes	Pycnonotidae	Decreasing	R
S49	Rock dove	*Columba livia*	Columbiformes	Columbidae	Decreasing	R
S50	Rose-ringed parakeet	*Psittacula krameri*	Psittaciformes	Psittacidae	Increasing	R
S51	Rufous treepie	*Dendrocitta vagabunda*	Passeriformes	Corvidae	Stable	R
S52	Scaly-breasted munia	*Lonchura punctulata*	Passeriformes	Estrildidae	Stable	R
S54	Spotted dove	*Spilopelia chinensis*	Columbiformes	Columbidae	Increasing	R
S56	Tricolored munia	*Lonchura malacca*	Passeriformes	Estrildidae	Stable	R
S57	Western koel	*Eudynamys scolopaceus*	Cuculiformes	Cuculidae	Stable	R
S59	White-breasted waterhen	*Amaurornis phoenicurus*	Gruiformes	Rallidae	Unknown	R

R resident

Table 19 Notable piscifauna observed in PL

Species code	Order	Family	Scientific name	Common name (English)	Common name (Bengali)	Population trend
SP1	Cypriniformes	Cyprinidae	*Hypophthalmichthys molitrix*	Silver carp	Silver carp	DE
SP2			*Aristichthys nobilis*	Bighead carp	Bighead carp	DE
SP3			*Labeo bata*	Bata	Bata	UN
SP4			*Catla catla*	Catla	Catla	UN
SP5			*Cyprinus carpio*	Common carp	American rui	UN
SP6			*Ctenopharyngodon idella*	White Amur	Grass carp	UN
SP7			*Labeo calbasu*	Orangefin labeo	Kalibaus	UN
SP8			*Cirrhinus mrigala*	White carp	Mrigal	DE
SP9			*Amblypharyngodon mola*	Mola carplet	Murala	ST
SP10			*Puntius puntio*	Puntio barb	Punti	UN
SP11			*Labeo rohita*	Rohu	Rui	UN
SP13	Perciformes	Cichlidae	*Oreochromis niloticus*	Nile tilapia	Nilotica	UN
SP14		Channidae	*Channa punctatus*	Spotted snakehead	Lata	UN
SP15	Siluriformes	Clariidae	*Clarias batrachus*	Philippine catfish	Magur	UN

DE decreasing, *UN* unknown, *ST* stable

7 Developmental Activities Based on Pitlakes

Under careful management programmes ensuring optimum biotic and abiotic characteristics, PL and their resources can directly and indirectly promote developmental activities. Developmental activities that can be based on RCF PL under the existing conditions are suggested in the following flow chart (Fig. 8; Table 20), which may prove worthwhile for consideration. Such implementation can generate employment and improve the economic conditions of the local people most of whom lie below the poverty level. However, care must be taken to formulate the PL-friendly and sustainable developmental programmes since the use of water resources, fisheries, tourism, recreation, etc. is likely to prove detrimental.

Keeping in mind the present need of the hour to conserve natural resources, PL restoration projects need to be implemented more collaterally with sustainable utilization of its resources. Moreover, extensive and intensive field and laboratory studies in correlation with information obtained from application of remote sensing technology on PL of the RCF can not only rationalize resource utilization but also

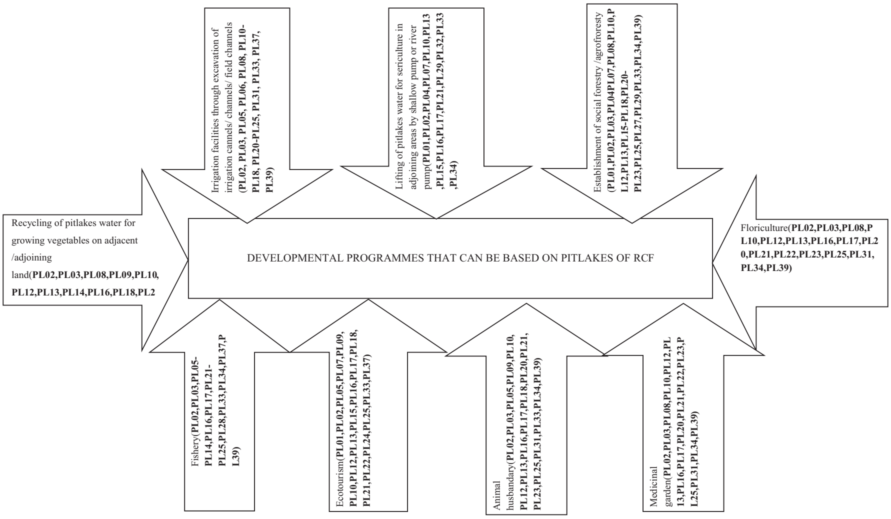


Fig. 8 Developmental programmes that can be based on pitlakes of RCF
Legend of pitlake codes: PL01, Chora pitlake; PL02, Joyalbhanga 1 pitlake; PL03, Vatas 1 pitlake; PL04, Katapahari pitlake; PL05, Amdia pitlake; PL06, Samdi pitlake; PL07, Dalmia pitlake; PL08, Dalmia pitlake; PL09, Bonbedi pitlake; PL10, Alkusa Gopalpur pitlake; PL11, Sikhdaspur pitlake; PL12, Jambad 5 pitlake; PL13, Jambad 4 pitlake; PL14, Jambad bottom-up pitlake; PL15, Western Kajora pitlake; PL16, Atewal pitlake; PL17, Khadan Kali pitlake; PL18, Babuisol Sibmandir pitlake; PL19, Ramnagar pitlake; PL20, Belpahari Kottadihi pitlake; PL21, Dalurbandh pitlake; PL22, Nagrakonda pitlake; PL23, Pathaldanga pitlake; PL24, Nimcha Harabanga pitlake; PL25, Real Kajora pitlake; PL26, Chakrambati pitlake; PL27, Dhanderdihi 1 pitlake; PL28, Dhanderdihi 2 pitlake; PL29, Dhandadihi 3 pitlake; PL30, Porasia Khadan pitlake; PL31, Babuisol Colony pitlake; PL32, Kumardihi pitlake; PL33, Kumardihi Old OCP pitlake; PL34, Joyalbanga 2 pitlake; PL35, Sankarpur pitlake; PL36, Gunjan Ecological Park pitlake; PL37, Nimcha Damali Harabanga pitlake; PL38, Patmohana Ranisayar pitlake; PL39, Vatas 2 pitlake; PL40, Chapuikhash pitlake

help in identifying areas of uncertainty, crisis and problems so that safety, restorative and mitigatory measures can be formulated for practical application. Such an integrated approach can provide scope for protecting the environment from future disaster and strengthen the economy. This work would be considered successful if the findings are used in the future for formulating strategies for both ecological welfare and economic development.

We have inventoried forty 40 PLs and among them irrigation facilities can be started in 24 PLs. After analysis of PL water quality and questionnaire survey of local stakeholder, we have recorded that fishery can be started in 25 PLs. The adjoining areas of 23 PLs are suitable for social forestry or agroforestry, and 16 PLs are suitable for floriculture and medicinal garden. Eighteen PLs can be transformed into an ecotourism centre. The adjoining areas of 18 PLs can be used for animal husbandry, and the adjoining areas of 16 PLs can be used for vegetable garden.

Table 20 Developmental activities based on PL (PL wise)

Serial no.	Name of the PL	Irrigation facilities	Sericulture in adjoining areas	Social forestry/ agroforestry	Fishery	Floriculture	Medicinal garden	Animal husbandry	Ecotourism	Recycling of PL water for growing vegetables on adjacent/adjoining land
PL01	Chora PL		√	√					√	
PL02	Joyalbhanga 1 PL	√	√	√	√	√	√	√	√	√
PL03	Vatas 1 PL	√		√	√	√	√	√		√
PL04	Katapahari PL		√	√						
PL05	Amdia PL	√			√			√	√	
PL06	Samdi PL	√			√					
PL07	Dalmia PL		√	√	√				√	
PL08	Bamna PL	√		√	√	√	√			√
PL09	Bonbedi PL				√			√	√	√
PL10	Alkusa Gopalpur PL	√	√	√	√	√	√	√	√	√
PL11	Sikhdaspur PL	√			√					
PL12	Jambad 5 PL	√		√	√	√	√	√	√	√
PL13	Jambad 4 PL	√	√	√	√	√	√	√	√	√
PL14	Jambad bottom-up PL	√			√					√
PL15	Western Kajora PL	√	√	√	√				√	
PL16	Atewal PL	√	√	√	√	√	√	√	√	√
PL17	Khadan Kali PL	√	√	√	√	√	√	√	√	
PL18	Babuisolsib Mandir PL	√		√				√	√	√
PL20	Belpahari Kottadihi PL	√		√		√	√	√		√
PL21	Dalurbandh PL	√	√	√	√	√	√	√	√	√
PL22	Nagrakonda PL	√		√	√	√	√		√	√
PL23	Pathaldanga PL	√		√	√	√	√	√		

PL24	Nimcha Harabanga PL	√			√				√	
PL25	Real Kajora PL	√		√	√	√	√	√	√	√
PL27	Dhanderdihi 1 PL			√						
PL28	Dhanderdihi 2 PL				√					
PL29	Dhandadihi 3 PL		√	√						
PL31	Babuisol Colony PL	√				√	√	√		
PL32	Kumardihi PL		√							
PL33	Kumardihi Old OCP PL	√	√	√	√			√	√	√
PL34	Joyalbanga 2 PL		√	√	√	√	√	√		
PL37	Nimcha Damali Harabanga PL	√			√				√	
PL39	Vatas 2 PL	√		√	√	√	√	√		√

8 Utilitarian Aspect of Pitlake Resources

Utilization profile of PL measured during the study period is tabulated in Table 21. In most of the PLs, multiple uses were observed. Most of the uses were proportionately related with the age of the PL. PL aged over 20–30 years turned naturally into wetland ecosystem harbouring a good amount of aquatic biota, excellent water quality and stabilized embankment. All of these attributes in recent decades produce some good number of PLs having multifarious prospect.

Our study revealed a total of 13 major uses of PL in RCF, WB region. Around 7 uses/PL (mean 6.47) were observed with a maximum of 11 uses/PL and a minimum of 1 use/PL. Recreational fishing by villagers was the most frequent use which was observed in 34 PLs (89.47%) followed by pisciculture (commercial fishing) in 18 PLs (47.37%).

Thirty-three PLs (86.84%) were used for chiefly domestic purpose. Livestock bathing (12 PLs, 31.58%), religious use (15 PLs, 39.47%) and aesthetic use (27 PLs, 71.05%) were some of the rigorously performed practices in these study sites.

Table 21 Utilization profile of PL measured during the study period

Category	Subcategory	Rel. frequency per category (%)
Piscicultural use	Absent	52.63
	Present	47.37
Recreational fishing use	Absent	10.53
	Present	89.47
Irrigational use	Absent	76.32
	Present	23.68
Domestic use	Absent	13.16
	Present	86.84
Livestock bathing use	Absent	71.05
	Present	31.58
Religious use	Absent	60.53
	Present	39.47
Drinking water use	Absent	76.32
	Present	23.68
Aesthetic use	Absent	28.95
	Present	71.05
Vehicle washing use	Absent	76.32
	Present	23.68
Food source use	Absent	7.89
	Present	92.11
Thatching material use	Absent	65.79
	Present	34.21
Fodder use	Absent	50.00
	Present	50.00
Water supply use	Absent	71.05
	Present	28.95

In nine PLs (23.68%), we observed excellent and efficient irrigation chiefly for water supply and agriculture in the vicinity.

Among the other various practices, different food source collections (e.g., *Trapa* cultivation, edible vegetables, fishes, fruits) comprised the major use (35 PLs, 92.11%) followed by fodder use (19, 50%) and thatching material use (13, 34.21%). One of the vital resources of these PLs is “water”, and we observed proper and well-organized water supply system in 11 PLs (28.95%). Drinking water use and vehicle washing were the less frequent practices in these PLs (9, 23.68%) which were performed in selected PL only.

Depths of PL appreciably direct different uses such that there is a trend to use lower depth PL in greater magnitude. Recreational fishing (0.8796), food source use (0.8551), domestic use (0.8510) and aesthetic use (0.7204) are some of the notable usages which were exclusively found in PL with lower mean depth of water column, whereas deeper PLs were used for mostly irrigational use (0.1429), vehicle washing (0.2980) and water supply (0.4061).

During this entire tenure of work, a very brief idea about the current scenario of the PL with special emphasis on limnology, biodiversity, use pattern, etc. in this region is generated. Further extensive research, investigation, seasonal monitoring and pilot-scale study with socioeconomic purview in the next phase of study will produce valuable research findings.

9 Potentiality of Pitlakes for Irrigation/Agriculture

Table 22 depicts the potentiality of PLs for irrigation in Pandaveswar block.

10 Threats/Problems Faced by Pitlakes

Table 23 depicts the different threats which affect the PL in this region. It is observed that soil filling and fly ash filling are the most important drivers for PL stability, sustenance and survival. Presently, ten PLs require proper management and conservation planning for long-term benefits to the human society.

11 Pitlakes and Ecological Sustainability

The impact of large-scale mining on the landscape is a permanent legacy of industrialization and unique to the Anthropocene. Thousands of lakes created from the flooding of abandoned open-cut mines occur across every inhabited continent, and many of these lakes are toxic, posing risks to adjacent communities and ecosystems. sustainable plans to improve water quality and biodiversity in PLs do not exist due to (1) confusion as to the ultimate use of these lakes, (2) involvement of ecologists only after the lake is filled and (3) PL ecology struggling to reach the primary literature. An integrated approach to PL management engages ecologists in PL design,

Table 22 Potentiality of pitlakes for irrigation in Pandaveswar block

Serial no.	Source of water	Location can be irrigated	Approx. no. of beneficiary farmers and area	Distance from source	Details of scheme
1.	Shankarpur OCP at Shankarpur Mouza (PL35)	Shankarpur village	50 nos. (Area = 20 Ha)	1 km from water source	Water should be stored at the pond at that cultivated area
2.	Dalurbandh OCP at Dalurbandh Mouza (PL21)	Bilpahari Mouza	50 nos. (Area = 20Ha)	1.5 km from water source	Lifting of water from the OCP and irrigate at that area
3.	Kumardihi OCP and Kumardihi Old OCP at Kumardihi Mouza abandoned PL (PL32 and PL33)	Kumardihi Mouza	100 nos. (Area = 100Ha.)	1.5–2 km from OCP	From OCP water should be lifted at Sair pukur from where irrigation can be done
1.1.1.4.	Joalbhanga OCP, Purusatyampur OCP and Joyalbanga 2 PL at Joalbhanga Mouza (PL02 and PL34)	Mohal = 100 Ha. Dannya = 80 Ha. Sonabandhi = 80 Ha. Joalbhanga = 100 Ha.	350 nos. (Area = 360 Ha)	1–1.5 km from OCP	From OCP water should be lifted at Bara Sair pukur and Rai pukur, Darkagora ponds from where irrigation can be done

Source: Office of the Assistant Director of Agriculture, Andal, Burdwan

Table 23 Threats/problems faced by PLs

PL code	PL name	Threats/problems
PL01	Chora PL	Plants cover the maximum waterbody
PL06	Samdi PL	Soil filling
PL08	Bamna PL	Excessive use of water for road construction
PL09	Bonbedi PL	Chances of land sliding
PL11	Sikhdaspur PL	Excessive growth of *Salvinia* sp.
PL19	Ramnagar PL	Chances of land sliding
PL20	Belpahari Kottadihi PL	Soil filling
PL26	Chakrambati PL	Fly ash filling
PL35	Sankarpur PL	Soil filling
PL40	Chapuikhas PL	Scarcity of water in premonsoon and post-monsoon season

prioritizing ecological progress and passive treatment in mine closure planning and ultimately empowering communities with post-mining options.

Nevertheless, in an era of increasing recognition of environmental and social damage from an ever-growing scale of mining coupled with increasing corporate social conscience for these activities, the mining industry usually works to reduce operational risk and retain its social licence to mine the community resource through a variety of strategies. Many of these strategies are focused around the concept of sustainability, including creating sustainable livelihoods (employment, community development and infrastructure), optimizing resource use and final closing of mining operations in a manner that minimizes social and environmental harm, and yet retain future options for the lease (BHP Billiton Plc 2005; Rio Tinto Plc 2005; Ashoka et al. 2017). Although understandings do vary (Mudd 2005), sustainable mining commonly incorporates "the evaluation and management of the uncertainties and risks associated with earth resource development" (Meech 1999). This sustainability definition also fits well with the understanding of most government authorities concerned with the regulation of environmental and social impacts of mining (Mudd 2004). As a result of this regulatory focus, sustainability of mining leases is often solely concerned with minimizing the immediate and long-term risks to all stakeholders concerned (e.g., the social and ecological environment surrounding the mine). One potential legacy of open-cut mining is the mining pit(s) left after rehabilitation operations are completed.

12 Conclusion

PLs form when surface mines close and open pits filled with water, either through groundwater recharge, surface water diversion or active pumping. The primary goals of this study was to prepare an inventory of PLs in RCF, West Bengal, India, along with the status of water quality in these PLs for promoting sustainable utilization of the PL resources for socioeconomic development of the local stakeholders in due course of time. A comprehensive water quality and biological monitoring programme is strongly recommended for these PLs in order to be able to predict and manage risks and best utilize the opportunities provided by the PLs for the RCF region economy.

Based on different aspects of PL like subdivision, block, area of mining, major uses, major problem and secondary livelihood like fishing activity and presence or absence of migratory birds, the PL can be classified into small groups. A consecutive 2-year study of physicochemical parameters of water and soil was recorded at 27 selected mine PLs to understand its quality.

Biological resources of all PLs were studied throughout the study period. A total of 30 species belonging to 21 families of frequent hydrophytes/marginal plant species dominating these PLs were observed. successional stages of plant species were noticed and grouped in accordance with their growth pattern. Effective aquatic life supporting environment have been observed in these PLs which is also supported by the rich avifaunal and piscifaunal resources in and around these PLs. In Most of the PLs, multiple uses were observed. Most of the uses were proportionately related with the age of the PL. PLs aged over 20–30 years turned naturally into wetland ecosystem harbouring a good amount of aquatic biota, excellent water quality and stabilized embankment. All of these attributes in recent decades produce some good number of PLs having multifarious prospect.

The benefits of the PL were received by the local residents across different socio-economic backgrounds. The activities of the local residents were focussed across the different age and gender groups, which can pollute and contaminate the pit water and PL areas.

13 Pitlakes: Future Ecological Perspectives

Ecological approaches to develop PL ecosystems may assist in clearly articulating targets for the long-term sustainability of PLs. Such ecological versus physicochemical-driven approaches also recognize mine water-affected landscapes such as PLs as more than a geochemical environment, with consequent further (and often simple) requirements for fundamental limnological and ecological processes also needing to be addressed if restoration to a representative functional ecosystem is to be successful. although it is likely that their broad environmental requirements for food and habitat will be very similar to those in natural systems, PL biota and their ecological requirements remain rarely studied and poorly understood. As such, there remains a pressing need for catchment-scale rehabilitation attempts of PLs to move towards development of aquatic ecosystems as a best practice. These restoration attempts are likely to initially fall short of attaining satisfactory ecosystem values due to a lack of knowledge of general PL formation and ecological processes, as well as intrinsic site-specific considerations. However, monitoring and ad hoc investigation studies of combined physicochemical and ecological characteristics of these early attempts will provide fertile insight for future restoration attempts.

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Phytoremediation: An Advance Approach for Stabilization of Coal Mine Wastelands

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Abstract

Wastelands (WLs) are characterized by the habitats that have lost the power to exhibit resilience in a way to revert back the process of degradation while conserving the biota and the stability the habitat conditions. Revegetation is one of the widely used techniques for stabilization of dump, thereby maintaining ecological equilibrium in the area. Phytoremediation (PR) strategies involve the use of different plant species in combating the alterations in the environmental conditions induced due to natural and artificial causes. Considering the importance of all these perspectives in optimization of opencast coal mined areas, the present work was planned and executed in selected sites of Raniganj Coalfield areas in Burdwan district of West Bengal. On the basis of the observation on the plant species assemblages of the WL, it is apparent that the landscape is heterogeneous with differences in the quality of the patches represented through the species of plants. Heterogeneity was noticed due to different abundance of plant species in different wastelands. The growth pattern of the nine plants in pot culture over the period of 1 year reflects the potentials of the plants to be incorporated in the restoration strategy of the WL subjected to coal mining activity in the past. The growth of neem (*Azadirachta indica*) was not same as that of Indian laburnum (*Cassia fistula*) or shisham (*Dalbergia sissoo*), which however reflects the varying level of importance of these species in organizing the community. Although the differences in the species-specific growth pattern were demonstrated in the pot culture, the ability to tolerate wide variations in the soil conditions provides evidence in their use in PR of the WL. Among the plant species, the differences in the cadmium (Cd) and mercury (Hg) adsorption varied for Indian laburnum significantly reflected through the t-test. The selected plant species considered in the study will be able to reduce the metal load and modulate the soil conditions of the WL, thereby facilitating the process of restoration of the degraded ecosystems of the concerned geographical area.

Keywords

Coal mine · Ecorestoration · Phytoremediation · Revegetation · Raniganj · Wastelands

Abbreviations

ALIN	Average length of internode
Cd	Cadmium
DA	Discriminant function analysis
Hg	Mercury
MS	Mine spoil
NAB	Number of axillary bud
NB	Number of branches
NN	Number of node
PR	Phytoremediation
WL	Wasteland

1 Introduction

At the early stages of an ecosystem development, soils constitute a critical controlling component. Without the progress of natural processes of soil development, ecosystems would remain in an underdeveloped condition. Mine spoil (MS) heaps are composed of coarse rocks excavated during the deep coal mining operations and associated coal processing. Mining activity changes natural condition of landscape and biological communities (Down and Stocks 1977; Ahmad and Singh 2004; Sarma 2005; Kiro et al. 2017; Datta et al. 2017; Kumar et al. 2017; Raj et al. 2018). Natural plant communities get disturbed due to mining activities, and following the mining, the habitats become impoverished presenting a very rigorous condition for its growth (Jhariya et al. 2013, 2016).

Mining operations, which involve extraction of minerals from the earth's crust, are second after agriculture as the world's oldest and important activity. Mining tends to make a notable impact on the environment, and the impact varies in severity depending on whether the mine is working or abandoned, the mining methods used and the geological conditions (Bell et al. 2001; Mondal et al. 2014; Mahalik and Satapathy 2016). Due to unscientific mining process, reduction of forest cover; erosion of soil in a great scale; pollution of air, water and land; and reduction in biodiversity had occurred (UNESCO 1985). The problems of waste rock dumps become devastating to the landscape around mining areas (Ghose 1996; Dutta and Agrawal 2002; Banerjee et al. 2004; Singh and Singh 2006; Ekka and Behera 2011; Meena et al. 2016).

Increasing growth pattern of each plant species of wastelands (WLs) enacts as a positive mode of revegetation strategy. A total number of ten plant species, viz. *Acacia mangium* (mangium), *Acacia cracicarpa (northern wattle)*, *Cassia siamea (kassod)*, *Dendrocalamus strictus (male bamboo)*, *Dalbergia sissoo (Shisham)*, *Gliricidia sepium (Mexican lilac)*, *Pterocarpus santalinus (red sandalwood)*, *Sesbania grandiflora (Agati)*, *Stylo hamate (Caribbean stylo)* and *Stylo scabra (shrubby stylo),* were selected for the evaluation of growth performance in pot and filled condition in Lalmatia coalfield, Jharkhand, India. It was noticed that the morphometric assessment in terms of shoot height and number of branches under the influence of treatment ($T_{1–9}$) indicates that the effect of different treatments on growth of the raised plant over the control (T_1) in poly bags under green house was appreciable. All the plants showed maximum increase in shoot height and number of branches in tripartite combination (Arshi 2017).

In the context of increasing mined land degradation, both the ecological and economic imperatives demand that restoration of land be prioritized, and for that it is required to maintain an equilibrium between development and environment through implementation of strategies of ecorestoration.

In view of this, the present study aims to formulate a strategy for ecorestoration of opencast coal mining sites through inoculation of appropriate amendments in the mine spoils to transform them into soil and revegetation by appropriate tree species selected through pot culture experimental trials using spoils with and without amendments. As a prerequisite to such a programme, a precise account of the vegetation that tend to develop in the mine-affected areas needs to be prepared as the index of the successional trend and natural autophytoremediation (PR) process in progress. Moreover, for ecorestoration there is a collateral need to assess physicochemical properties of the underlying substratum in temporal scale and optimize the same, if necessary, with suitable amendments.

2 Mine Wasteland: Definition, Types and Genesis

WL literally means that land or area of land on which not much can grow or which has been spoiled in some way so as to become unsuitable for cultivation. WLs are synonymous with drastically disturbed lands where the native vegetation and animal communities have been removed and the topsoil has been lost, altered and buried. Such lands will not become naturally rehabilitated within the life of time of man through normal succession process (Chandra 1992; Sagar et al. 2015). In practice, WL can be defined as "areas where current biomass production seldom exceeds 20 per cent of its overall potential".

From a resource point of view, a WL is that land which is presently lying either unused or cannot be used to its optimum potential due to some constraints. WL thus is an index of the country's use strategy of land resource.

2.1 Origin of Wastelands

Degradation of land takes place due to various reasons such as deforestation, unscientific cultivation, salinity, alkalinity, waterlogging, wind erosion, etc. The degradation of environment in dry land areas is basically attributable to the increasing biotic pressure for the fragile ecosystems in the absence of adequate investments and appropriate management practices to augment and conserve the land and water resources. Maximum WLs are created due to clearing of natural forests.

2.2 Types of Wastelands

National Wasteland Development Board in 1985 classifies WL into two categories:

1. Cultivable WL
2. Uncultivable WL

The cultivable WLs have been classified into:

(a) Gullied and/or ravenous lands
(b) Undulating land without shrub;
(c) Surface waterlogging land and marsh

(d) Salt-affected land
(e) Shifting cultivation area
(f) Degraded forestland
(g) Degraded pasture/grazing land
(h) Degraded forest plantations
(i) Strip lands
(j) Sand dunes
(k) Mining/industrial WL

Uncultivable WLs which cannot be used for vegetation are classified as (a) brown rocky/stony/shut of rocks, (b) steep sloppy areas and (c) snow-covered and/or glacier lands.

3 Special Emphasis on Coal Mine Wasteland

Mining activity imposes serious damage to the landscape and biological communities and its severity profoundly noticed in mining status, methods and condition of geological position (Bell et al. 2001; Singh et al. 2007; Sadhu et al. 2012; Mondal et al. 2014). Mine WL generally comprises the bare stripped area, loose soil piles, waste rock and overburden surfaces, subsided land areas and other degraded land by mining facilities, among which the waste rocks often pose extreme stressful conditions for restoration. Disruption of soil components such as soil horizons and structure, soil microbe populations and nutrient cycles inhibits the aesthetic value of the landscape which results in vegetation destruction and deteriorates soil profile (Kundu and Ghose 1997; Sheoran and Sheoran 2009; Mbaya and Hashidu 2013). Soil erosion, air and water pollution, toxicity, geo-environmental disasters, loss of biodiversity, loss of economic wealth, etc. are the major effects of mine wastes (Wong and Bradshaw 1982; Sheoran et al. 2008; Singh et al. 2014; Ashoka et al. 2017). The mineral extraction process must ensure return of productivity of the affected land. With rising environmentalism, synchronized post-mining reclamation of the degraded land has become an included part of the whole mining range (Ghose 1989, 2001, 2004; Haigh 1993).

4 Spoil Formation and Its Characteristics

Opencast mining is a developmental activity, which is bound to damage the natural ecosystem by several mining activities. During opencast mining, the overlying soil is removed, and the fragmented rock is heaped in the form of overburden dumps (Ghosh 2002). Dump materials are left over the land in the form of overburden dumps. These occupy a large amount of land, which loses its original use and generally gets soil qualities degraded (Barapanda et al. 2001). As the dump materials are generally loose, fine particles from it become highly prone to blowing by wind.

These get spread over the surrounding fertile land and disturb plant's natural quality and growth of fresh leaves. It has been found that overburden dump top materials are usually deficient in major nutrients. Hence, most of the overburden dumps do not support plantation. The physicochemical properties of overburden dump materials are site specific and differ from one dump to another dump due to different geological deposit of rocks (Lovesan et al. 1998; Rai et al. 2011; Kumar et al. 2017a).

5 Physicochemical Characteristics of Coal Mine Spoil

To characterize the physical and chemical properties of the MS, samples were analysed for different parameters. Out of eleven, six physical parameters such as pH, soil conductivity, bulk density, particle density, porosity and water holding capacity and five chemical parameters like organic carbon, available nitrogen, available phosphate-phosphorous, available potassium and available sodium were analysed. The climate condition that prevails in the study area provides three seasons in a year, i.e. pre-monsoon (March to June), monsoon (July to October) and post-monsoon (November to February). Spoil samples were collected seasonally (Table 1). The materials used and methods followed during the course of studies are described below.

Table 1 Analytical methods of spoil analysis followed in the present work

SN	Parameters	Methods followed
1.	Soil pH	Electronic pH metre in 1:10 soil water suspension as described by Jackson (1972)
2.	Soil conductivity (μs)	Electronic conductivity metre in 1:2 soil water suspension as described by Jackson (1972)
3.	Bulk density (g/cm^3)	Gupta (2004)
4.	Particle density (g/cm^3)	Black (1965)
5.	Porosity (%)	Black (1965)
6.	Water holding capacity (%)	Saxena (1998)
7.	Organic carbon (%)	Volumetric analysis method (Walkley 1947) as described by Muhr et al. (1965)
8.	Available nitrogen (kg ha^{-1})	Kjeldahl method as described by Subbiah and Asija (1956)
9.	Available phosphorus (kg ha^{-1})	Olsen's method as described by Olsen et al. (1954)
10.	Available potassium (kg ha^{-1})	Flame photometer method as described by Black (1965)
11.	Available sodium (kg ha^{-1})	Flame photometer method as described by Black (1965)

6 Indigenous Vegetation Structure

The problems of overburden dumps during mining become devastating to the landscape; as a result, natural plant communities get disturbed and the habitats become impoverished, presenting a very rigorous condition for plant growth.

The possible effects of the variability of the soil quality can translate into differential colonization and establishment of the plant species. The variability may facilitate the heterogeneity of the plant species assemblages in the concerned sites which may be reflected through the analysis of the vegetation of the sites.

The observations on the plant diversity and the soil features in the selected sites of the WL of Raniganj Coalfield, West Bengal, revealed the presence of at least 114 different angiosperms belonging to 40 families (Table 2). Considerable differences in the relative abundance of the plant species were observed that substantiates the differences in the colonization ability and the niche requirements of the species.

Table 2 The plant species observed in course of sampling the selected sites of the WL abandoned colliery of Raniganj, West Bengal, India

Sl. No.	Plant name	Abbreviation used in text	Relative abundance
Family: Acanthaceae			
1	*Andrographis echioides* Nees	ANEC	0.06 ± 0.03
2	*Andrographis paniculata* Nees	ANPA	0.24 ± 0.05
3	*Ruellia tuberosa* L.	RUTU	0.09 ± 0.04
Family: Agavaceae			
4	*Agave sisalana* Perrine	AGSI	0.10 ± 0.04
Family: Aizoaceae			
5	*Trianthema portulacastrum* L.	TRPO	0.04 ± 0.02
Family: Alangiaceae			
6	*Alangium lamarckii* Thwaites	ALLA	0.19 ± 0.04
Family: Amaranthaceae			
7	*Alternanthera pungens* Kunth	ALPU	0.05 ± 0.02
8	*Alternanthera sessilis* (L.) R.Br. ex DC.	ALSE	0.02 ± 0.02
9	*Alternanthera tenella* Colla	ALTE	0.22 ± 0.06
10	*Amaranthus spinosus* L.	AMSP	0.67 ± 0.13
11	*Amaranthus viridis* L.	AMVI	0.59 ± 0.09
12	*Gomphrena celosioides* Mart.	GOCE	0.21 ± 0.04
Family: Apocynaceae			
13	*Alstonia scholaris* (L.) R.Br.	ALSC	0.06 ± 0.04
14	*Thevetia neriifolia* Juss. ex Steud.	THNE	0.05 ± 0.02
Family: Arecaceae			
15	*Phoenix sylvestris* (L.) Roxb.	PHSY	0.18 ± 0.04
Family: Asclepiadaceae			
16	*Calotropis gigantea* (L.) W.T.Aiton	CAGI	2.13 ± 0.21
17	*Calotropis procera* W.T.Aiton	CAPR	0.38 ± 0.07

(continued)

Table 2 (continued)

Sl. No.	Plant name	Abbreviation used in text	Relative abundance
18	*Hemidesmus indicus* (L.) R.Br. ex Schult.	HEIN	0.11 ± 0.04
19	*Pergularia daemia* (Forssk.) Chiov.	PEDA	0.09 ± 0.03
Family: Asteraceae			
20	*Cnicus wallichii* Hook.f.	CNWA	0.57 ± 0.24
21	*Eclipta alba* (L.) Hassk.	ECAL	0.29 ± 0.06
22	*Mikania scandens* (L.) Willd.	MISC	0.10 ± 0.04
23	*Spilanthes paniculata* Wall.	SPPA	0.18 ± 0.05
24	*Tridax procumbens* L.	TRPR	0.51 ± 0.09
25	*Vernonia cinerea* (L.) Less.	VECI	0.64 ± 0.11
26	*Xanthium strumarium* L.	XAST	0.80 ± 0.12
27	*Eupatorium odoratum* L.	EUOD	0.82 ± 0.11
Family: Capparaceae			
28	*Cleome gynandra* L.	CLGY	0.16 ± 0.05
29	*Cleome viscosa* L.	CLVI	0.19 ± 0.05
Family: Combretaceae			
30	*Terminalia arjuna* (Roxb. ex DC.) Wight & Arn.	TEAR	0.02 ± 0.01
Family: Commelinaceae			
31	*Commelina benghalensis* Forssk.	COBE	0.06 ± 0.02
Family: Convolvulaceae			
32	*Ipomoea maxima* (L.f.) Sweet	IPMA	0.03 ± 0.02
33	*Ipomoea pes-tigridis* L.	IPPE	0.06 ± 0.02
34	*Ipomoea pinnata* Hochst. ex Choisy	IPPI	0.06 ± 0.03
Family: Cucurbitaceae			
35	*Coccinia cordifolia* Cogn.	COCO	0.33 ± 0.06
36	*Trichosanthes cucumerina* L.	TRCU	0.04 ± 0.02
Family: Cyperaceae			
37	*Cyperus rotundus* L.	CYRO	0.06 ± 0.02
38	*Kyllinga monocephala* Muhl.	KYMO	0.20 ± 0.06
Family: Euphorbiaceae			
39	*Acalypha indica* L.	ACIN	0.19 ± 0.05
40	*Croton bonplandianus* Baill.	CRBO	0.96 ± 0.16
41	*Emblica officinalis* Gaertn.	EMOF	0.05 ± 0.02
42	*Euphorbia antiquorum* L.	EUAN	0.03 ± 0.02
43	*Euphorbia hirta* L.	EUHI	0.17 ± 0.04
44	*Jatropha curcas* L.	JACU	0.06 ± 0.02
45	*Jatropha gossypiifolia* L.	JAGO	0.75 ± 0.10
46	*Phyllanthus amarus* Schumach. & Thonn.	PHAM	0.33 ± 0.07
Family: Fabaceae			
47	*Acacia arabica* (Lam.) Willd.	ACAR	0.33 ± 0.09
48	*Acacia auriculaeformis* Benth.	ACAU	1.56 ± 0.18
49	*Acacia nilotica* (L.) Delile	ACNI	0.05 ± 0.02
50	*Atylosia scarabaeoides* (L.) Benth.	ATSC	0.02 ± 0.02

(continued)

Table 2 (continued)

Sl. No.	Plant name	Abbreviation used in text	Relative abundance
51	*Butea monosperma* (Lam.) Taub.	BUMO	0.08 ± 0.03
52	*Cassia alata* L.	CAAL	0.63 ± 0.11
53	*Cassia fistula* L.	CAFI	0.08 ± 0.03
54	*Cassia obtusifolia* L.	CAOB	0.33 ± 0.07
55	*Cassia siamea* Lam.	CASI	0.06 ± 0.03
56	*Cassia sophera* L.	CASO	0.36 ± 0.11
57	*Cassia tora* L.	CATO	1.03 ± 0.14
58	*Crotalaria pallida* Aiton	CRPA	0.02 ± 0.01
59	*Dalbergia sissoo* Roxb.	DASI	1.07 ± 0.12
60	*Desmodium gangeticum* (L.) DC.	DEGA	0.02 ± 0.02
61	*Pongamia glabra* Vent.	POGL	0.44 ± 0.09
62	*Tephrosia purpurea* (L.) Pers.	TEPU	0.52 ± 0.10
63	*Tephrosia villosa* (L.) Pers.	TEVI	0.37 ± 0.08
64	*Teramnus labialis* (L.f.) Spreng.	TELA	0.02 ± 0.01
Family: Flacourtiaceae			
65	*Flacourtia indica* (Burm.f.) Merr.	FLIN	0.06 ± 0.03
Family: Lamiaceae			
66	*Clerodendrum viscosum* Vent.	CLVIS	0.58 ± 0.09
67	*Gmelina arborea* Roxb.	GMAR	0.02 ± 0.01
68	*Hyptis suaveolens* (L.) Poit.	HYSU	0.44 ± 0.12
69	*Leonurus sibiricus* L.	LESI	0.17 ± 0.05
70	*Leucas aspera* (Willd.) Link	LEAS	0.18 ± 0.05
71	*Ocimum canescens* A.J.Paton	OCCA	0.29 ± 0.06
72	*Vitex negundo* L.	VINE	0.25 ± 0.04
Family: Malvaceae			
73	*Abutilon indicum* (L.) Sweet	ABIN	0.08 ± 0.03
74	*Sida acuta* Burm.f.	SIAC	0.56 ± 0.09
75	*Sida cordata* (Burm.f.) Borss.Waalk.	SICO	0.33 ± 0.06
76	*Sida cordifolia* L.	SICOR	0.11 ± 0.05
77	*Urena lobata* L.	URLO	0.25 ± 0.06
Family: Meliaceae			
78	*Azadirachta indica* A.Juss.	AZIN	1.08 ± 0.12
Family: Menispermaceae			
79	*Stephania japonica* (Thunb.) Miers	STJA	0.02 ± 0.01
Family: Mimosaceae			
80	*Albizia lebbeck* (L.) Benth.	ALLE	0.33 ± 0.07
Family: Moraceae			
81	*Ficus benghalensis* L.	FIBE	0.20 ± 0.04
82	*Ficus cunea* Steud.	FICU	0.30 ± 0.05
83	*Ficus religiosa* L.	FIRE	0.11 ± 0.03
Family: Myrtaceae			
84	*Syzygium cumini* (L.) Skeels	SYCU	0.10 ± 0.04
Family: Nyctaginaceae			

(continued)

Table 2 (continued)

Sl. No.	Plant name	Abbreviation used in text	Relative abundance
85	*Mirabilis jalapa* L.	MIJA	0.02 ± 0.01
Family: Papaveraceae			
86	*Argemone mexicana* L.	ARME	0.39 ± 0.09
Family: Pedaliaceae			
87	*Pedalium murex* L.	PEMU	0.02 ± 0.02
Family: Poaceae			
88	*Aristida adscensionis* L.	ARAD	0.17 ± 0.05
89	*Chloris barbata* Sw.	CHBA	0.06 ± 0.03
90	*Cynodon dactylon* (L.) Pers.	CYDA	3.49 ± 0.33
91	*Eragrostis coarctata* Stapf	ERCO	0.55 ± 0.10
92	*Eulaliopsis binata* (Retz.) C.E.Hubb.	EUBI	0.24 ± 0.05
93	*Heteropogon contortus* Beauv. ex Roem. & Schult.	HECO	0.25 ± 0.06
94	*Oplismenus compositus* P.Beauv.	OPCO	0.17 ± 0.05
95	*Panicum maximum* Jacq.	PAMA	0.07 ± 0.03
96	*Poa annua* L.	POAN	0.01 ± 0.01
97	*Saccharum munja* Roxb.	SAMU	2.34 ± 0.17
98	*Saccharum spontaneum* L.	SASP	3.17 ± 0.23
Family: Polygonaceae			
99	*Polygonum barbatum* L.	POBA	0.03 ± 0.02
Family: Rhamnaceae			
100	*Ziziphus oenoplia* (L.) Mill.	ZIOE	0.06 ± 0.02
Family: Rubiaceae			
101	*Dentella repens* J.R.Forst. & G.Forst.	DERE	0.07 ± 0.03
102	*Spermacoce hispida* L.	SPHI	0.03 ± 0.02
Family: Scrophulariaceae			
103	*Scoparia dulcis* L.	SCDU	0.27 ± 0.06
Family: Simaroubaceae			
104	*Ailanthus excelsa* Roxb.	AIEX	0.19 ± 0.05
Family: Solanaceae			
105	*Datura metel* L.	DAME	0.40 ± 0.07
106	*Physalis minima* L.	PHMI	0.04 ± 0.02
107	*Solanum nigrum* L.	SONI	0.10 ± 0.03
108	*Solanum sisymbriifolium* Lam.	SOSI	2.23 ± 0.24
109	*Solanum surattense* Burm.f.	SOSU	0.24 ± 0.05
Family: Tiliaceae			
110	*Triumfetta rhomboidea* Jacq.	TRRH	0.20 ± 0.06
Family: Ulmaceae			
111	*Holoptelea integrifolia* (Roxb.) Planch.	HOIN	0.12 ± 0.03
Family: Verbenaceae			
112	*Lantana camara* L.	LACA	0.33 ± 0.07
Family: Vitaceae			
113	*Cayratia trifolia* (L.) Domin	CATR	0.04 ± 0.02
Family: Zygophyllaceae			
114	*Tribulus terrestris* L.	TRTE	0.04 ± 0.03

7 Wasteland Reclamation Through Phytoremediation Technology

The fulfilment of the demands for coal may increase the destabilized conditions of the ecosystems in the land mining areas, which is contrary to the objectives of the sustainable development. Thus to continue with the coal extraction and reduce the damage to the terrestrial ecosystem, simultaneous monitoring and remediation strategies need to be adopted to keep the pace of the economic development without affecting the ecosystem balance of the concerned landscape. An increased concern for environment evoked concurrent land restoration strategy to keep the balance of resource exploitation and ecological balance (Jhariya et al. 2018a, b). PR strategies, including the augmentative plantation of desired species in the degraded ecosystems subjected to the coal extraction in the past, are promoted as a feasible alternative to restore the ecological balance and reclamation of the landscape. Thus assessment of the vegetation and soil quality followed by the selection of the plants for the ability to restore the ecosystem processes are essential to predict about the impact of coal mining and the prospective restoration of the degraded ecosystems (Jha and Singh 1991; Bradshaw 1997; Wong 2003; Kumar et al. 2017; Meena et al. 2014; Banerjee et al. 2018). In apprehension of PR as a prospective tool to restore the ecological stability of the concerned landscape, an attempt is made through the evaluation of vegetation and soil quality along with the growth assessment of selected plants using Raniganj, West Bengal, India, as a model geographical area.

8 Pot Experiment

8.1 Selection of Suitable Plant Species for Reclamation

Long-term monitoring field experiments were set up at Durgapur Government College campus garden in 2013–2014. In pot culture experiments, suitable tree species for revegetation of MS were screened. The feasibility of directly implanting the tree species on a pot as a means of revegetation of MS was evaluated. For selection of suitability of plant species for revegetation of MS, species characteristics such as adaptability of plant species to the particular physical and chemical conditions of MS and longevity of established plants were considered (Rodrigues 1996). Choice of multipurpose trees can be of economic and social significance (Montagnini et al. 1995; Sanchez et al. 1985; Nair 1989; Young 1989). The availability, growth, adaptability and longevity are important parameters in selecting suitable tree species for revegetation purpose. In the present context, the plants were selected in compliance with their indigenous nature and adaptation to the local ecological and climatic conditions, supported through the ecological survey of the concerned WL. The trial using multiple species will increase the chance of selecting the appropriate with higher probability than trials using single or few species.

Consistent to this proposition, the features that qualified the plant species for the present experimental study are:

(a) Adapted to grow, spread and reproduce under severe conditions
(b) Leguminous species to fix atmospheric nitrogen and ameliorate the soil by addition of organic matter through plant litter
(c) Fruit yielding trees to attract birds, butterflies and other forms of wildlife and also encourage soil fauna
(d) Plantation species with good economic, social and aesthetic value for local population
(e) Fast-growing indigenous and exotic species to accelerate plant succession
(f) Help in the control of erosion and stabilization of mine dump
(g) Fire hardy, unbrowsable and stress tolerant (Singh et al. 2004)

Thus the multifunctional role of the plants with the ability to tolerate the odd soil and ecological conditions of the WL formed the basis for selection in the present study. The nine plants considered for the present study are Indian laburnum, Aonla (*Emblica officinalis*), shisham, neem, karanj (*Pongamia glabra*), siris (*Albizia lebbeck*), Indian elm (*Holoptelea integrifolia*), earleaf acacia (*Acacia auriculiformis*) and mahogany (*Swietenia macrophylla*), all being collected and planted as saplings in the earthen pots.

8.2 Sapling Collection

Saplings of nine selected tree species were collected from Durgapur Forest Nursery (maintained by the Divisional Forest Officer, Durgapur Division), Muchipara, with due permission to procure the saplings for the study. Thirty healthy saplings of each species were collected from the nursery and transported to Durgapur Government College campus experimental garden. Upon reaching the experimental station, individual plant species were planted in each pot for acclimatization and subsequent initiation of the experiment. Five replicates of each selected tree sapling were set up under six treatments. Overall 270 saplings were planted for screening out to determine the growth pattern and prospective use in PR technology for restoration of the degraded WL.

8.3 Experimental Design

Following collection of the plant species and appropriate maintenance in the local conditions, selected numbers of the saplings were planted in earthen pots consisting of varied kinds of soil conditions. The experimental design followed the pattern of randomized block design where the nine plants in appropriate replicates were allowed to grow in the earthen pots consisting of soils mimicking the WL conditions. In this design, the soil types formed treatment variable with the six levels represented as (a) MS, (b) garden soil (for control), (c) MS + compost, (d) MS + husk, (e) MS + fly ash and (f) MS + chemical fertilizer.

Plant growth parameters like shoot length, number of node (NN), average length of internodes (ALIN), number of axillary bud (NAB) and number of branches (NB) were selected as response variables representing the increment in the size and the biomass of the plants. Changes in the height and branching pattern are regarded as indicators of the growth of the plants. For each plant species and soil conditions, five replicates were considered. During the initial phase consisting of a period of 4 weeks, if a particular sapling failed to exhibit growth represented through erected stem and no wilting, and yellow colouration of leaves, the particular plant was considered as a representative sample for the study. In case the sapling failed to exhibit the indication of the growth, it was rejected and not considered for further study. Thus, in the initial stage, the number of replicates considered remained quite high, which was reduced as a maintenance error or otherwise due to the logistic reasons. Throughout the study, at least five replicates of a particular plant species under particular soil condition were available for monitoring growth.

In pot culture techniques, each pot was filled with MS, garden soil and MS with different treatment manures, fertilizers, fly ash and husk separately, and 3-month-old saplings were transplanted in the pot. Healthy saplings of nine tree species were planted up with the onset of monsoon in 6 cm depth in pot at model garden of Durgapur Government College Campus. Each pot was measured with the height 25 cm and diameter 40 cm. Experiments were set up in completely randomized block design with five replications (Kulkarni et al. 2007). Growth characteristics were measured up to 12 months. Each specific technique of pot culture experiment was documented in plates.

8.4 Materials Used in Pot Experiments

The treatment material selection is the important phase to set revegetation technology and PR technique. Materials were selected on the basis of several characters: (i) NPK content, (ii) organic carbon content, (iii) availability of the material, (iv) effectiveness in field use and (v) previous use experience (based upon review and literature). Based upon the availability and cost and suitability in the field condition, four treatment components such as compost, husk, fly ash and chemical fertilizer were selected for establishing PR technique. Following treatments were given, such as (a) MS, (b) garden soil (for control), (c) MS + compost, (d) MS + husk, (e) MS + fly ash and (f) MS + chemical fertilizer.

8.5 Maintenance During Experiment

The experimental garden was maintained through regular watering and removal of weed from the pots. Special attention was taken to those plants which were affected by wandering herbivore insects and interference of human, animals, rainfall and high temperature. The conditions were maintained such that the growths of the plants are measured without any effects of extraneous variables.

9 Growth Performance After Reclamation

Plant growth comprises three distinct phenomena, i.e. increase of cell, longitudinal growth of the cell (maturation stage) and horizontal growth of the cell. To access the growth through morphological expression, some vegetative growth parameters were introduced for measurement of plant growth. The observations for the morphological growth attributes were taken at every month of study period from the treatment field. Data for shoot length, NN, number of internodes, NAB and NB were collected for monthly basis.

(i) *Length of shoot* – The plants from each pot were measured, and height of those plants was scaled from ground level to the tip of the stem (axillary bud).
(ii) NN – Node indicates leaf, branch, and axillary bud originated structure, i.e. how many leaves, branches or axillary bud bearing angles present in the shoot.
(iii) ALIN – Internode was calculated by the following formula: shoot length/no. of nodes.
(iv) NAB – Leaves and branches are originated from axillary buds. Such axillary buds were measured for each plant species. Axillary buds are directly proportional to the plant growth.
(v) NB – Branches of each plant species were counted during the survey period.

All the plants selected for the study exhibited growth reflected through the changes in the morphological features, monitored over the entire observation period of 1 year. The data revealed significant variations among the plant species in terms of the morphological features, reflected through the discriminant function analysis (DA) (Fig. 1). As portrayed in the biplot (Fig. 1e), the ordination of the plants remained significantly different except for neem and Indian laburnum pair. The significant variations among the plants were observed from the Fisher's distance (Fig. 1d). The relative contribution of the explanatory variables (morphological features) (Fig. 1f) to the extracted factors remained contrastingly different, observed through the standardized discriminant function coefficient. Wilks' λ value of 0.279 justified the discrimination of the plant species with approximately about 75% variations of the data being explained by the extracted factors F1 and F2 (Fig. 1c). The multivariate analysis was extended using the soil treatment conditions as explanatory variables for the observed differences in the plant morphological features irrespective of the species. As shown in Fig. 2, the DA enabled segregation of the soil conditions (treatments) significantly, suggesting that the changes in the morphological features of the plants were differentially affected by the soil conditions (Fig. 2f). The Fisher's distance between the treatments remained significantly different (Fig. 2c) among the treatment pairs excepting for the soil (S) and spoil and husk (SP+H) treatments. The contributions of the morphological variables (explanatory variables) to the observed variations in the soil conditions remained significant in terms of the standardized discriminant function coefficient (Fig. 2d). The morphological variables could be segregated in different coordinates as shown in the biplot Fig. 2e. The results indicate that the soil treatment conditions affected the

(a)

Wilks' Lambda	**0.279**
F (Observed value)	119.524
F (Critical value)	1.395
DF1	40
DF2	14069
p-value	< 0.0001
Alpha	0.05

(b)

	F1	F2	F3	F4	F5
Eigenvalue	0.744	0.419	0.237	0.117	0.046
Discrimination (%)	47.588	26.795	15.161	7.495	2.961
Cumulative %	47.588	74.383	89.544	97.039	100.000
Canonical correlations	0.653	0.543	0.438	0.324	0.210

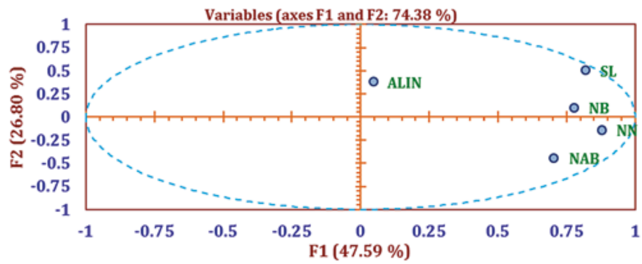
(c)

	CAF	EMO	DAS	AZI	POG	ALL	HOI	ACA
EMO	120.819							
DAS	287.905	215.305						
AZI	*9.159*	91.330	198.419					
POG	155.733	156.778	173.026	127.334				
ALL	45.121	101.555	177.367	29.870	47.639			
HOI	54.918	32.774	155.467	32.602	88.203	45.803		
ACA	290.182	104.410	194.969	219.118	218.385	196.582	160.141	
SWM	22.501	76.159	241.635	19.732	138.027	63.692	21.140	228.104

(d)

	F1	F2	F3	F4	F5
SL	0.355	**1.460**	0.659	-0.132	-0.734
NN	0.314	-0.882	-0.240	**1.058**	0.846
ALIN	-0.156	-0.285	-0.015	-0.237	**1.187**
NAB	0.281	-0.460	0.620	**-0.764**	-0.264
NB	0.396	-0.142	**-0.998**	-0.382	-0.004

(e)



(f)

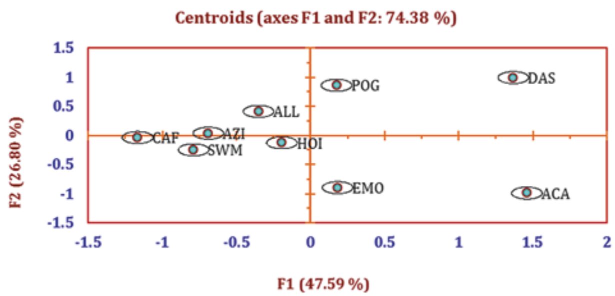


Fig. 1 The results of the DA for the observed variations in the response variables (plant species) against the explanatory variables (plant morphological features). (**a**) Wilks' lambda value, (**b**) eigenvalues and canonical correlations, (**c**) Fisher's distance (all except the value in *italic* is significant), (**d**) standardized canonical discriminant functions, (**e**) biplot with the ordination of the explanatory variables and (**f**) biplot with the ordination of the response variables

(a)

Wilks' Lambda	**0.911**
F (Observed value)	12.269
F (Critical value)	1.507
DF1	25
DF2	12000
P-value	< 0.0001
Alpha	0.05

(b)

	F1	F2	F3	F4
Eigenvalue	0.072	0.015	0.008	0.001
Discrimination (%)	74.931	15.670	8.131	1.268
Cumulative %	74.931	90.601	98.732	100.000
Canonical correlations	0.260	0.122	0.088	0.035

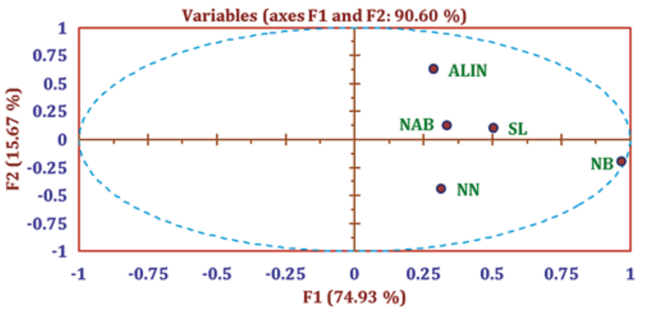
(c)

	S	SP	SP+C	SP+CF	SP+FA
SP	4.879				
SP+C	21.338	35.024			
SP+CF	3.986	14.604	12.330		
SP+FA	*3.125*	6.019	33.017	10.625	
SP+H	*1.989*	7.959	23.919	*2.428*	5.561

(d)

	F1	F2	F3	F4	F5
SL	0.504	0.101	0.344	0.524	0.585
NN	0.314	-0.442	0.671	0.424	0.275
ALIN	0.288	0.626	0.267	-0.414	0.531
NAB	0.334	0.123	0.734	0.407	-0.410
NB	0.970	-0.201	0.039	0.118	0.056

(e)



(f)

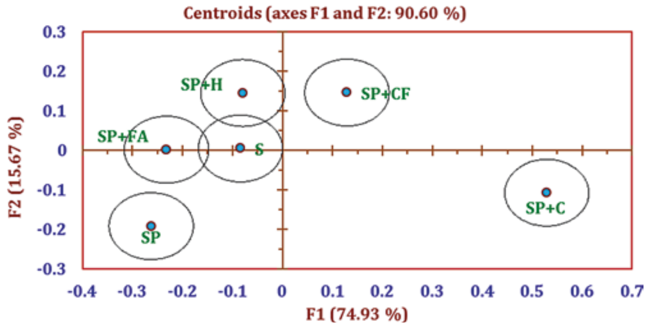


Fig. 2 The results of the DA for the observed variations in the response variables (plant morphological features) against the explanatory variables (soil treatment conditions). (**a**) Wilks' lambda value, (**b**) eigenvalues and canonical correlations, (**c**) Fisher's distance (all except the value in italic is significant), (**d**) standardized canonical discriminant functions, (**e**) biplot with the ordination of the explanatory variables and (**f**) biplot with the ordination of the response variables

morphological features of the plants irrespective of the taxonomic identity, and thus the growth of the plants was dependent on the treatments.

Nonetheless, the plants observed in the present study were capable of exhibiting growth in different soil conditions, mimicking the continuum of the soil quality observed in WL subjected to opencast coal mining in the past. Earlier studies on these plants have shown prospect of the use in revegetation of the altered soil conditions in abandoned coal fields of Jharia in India (Sheoran et al. 2010).

Globally, land mass subjected to coal mining activities in the past has been reclaimed through revegetation, though the selection of the native species has been given priority. The process reinstates the seral stages in the continuum of community development, and therefore the use of the grasses and herbs is less likely being useful. Instance from Poland (Woch et al. 2013; Piekarska-Stachowiak et al. 2014; Verma et al. 2015), England (Rostanski 2005) and China (Cheng and Lu 2005; Donggan et al. 2011; Huang et al. 2015; Zhang et al. 2015) suggests that the reclamation of the WL formed due to past mining activity can be augmented through the plantation of selected and desired plant species. Selection of the plant species is crucial in order to enhance the structuring of the community. The tolerance to the existing soil conditions remains an important criterion for selection of the plant species suitable for the restoration of the degraded landscape. In the present instance, the selected plant species, Indian laburnum, Aonla, shisham, neem, karanj, siris, Indian elm, earleaf acacia and mahogany, qualified as tolerant species, owing to their growth under the different treatment conditions. The growth of these plants reflects their tolerance to the soil conditions and supports their use in the restoration process of the degraded WLs that were subjected to active coal mining activities in the past. As reflected in the results of the present study, the use of these plant species in the PR of the WL through active plantation may restore the WL created through coal mining activities in the past.

10 Heavy Metal Accumulation Effect

The heavy metal accumulation capability of the nine plant species was assessed using cadmium (Cd) and mercury (Hg) as model metals. In toxicological parlance as well as for the physiology of biota, Cd and Hg are considered as toxic, interfering with the physiological, biochemical and genetic process of biota. Mining activities add Cd and Hg in the soil, thereby enhancing their entry in the food chain of the concerned ecosystem. Reducing the heavy metals from the soil will reduce their recurrence in higher magnitude in the different trophic levels. Bioaccumulation by plants of terrestrial ecosystems delinks the flow of the metals through the trophic levels. Thus, PR strategy using the leguminous plants can be a way of reducing the availability of the heavy metals in the ambient environment. In order to estimate the amount of the metal load present in the plant tissue and the soil, selected number of plants was uprooted from each of the treatments. In all instances, the preparations were made to evaluate the heavy metal content in the plant tissue using at least three replicates from six different treatments. The data were recorded against Cd and Hg separately.

The amount of heavy metal adsorbed in the plant tissues remained considerably different with respect to the soil treatment conditions (Fig. 3), as well as on the basis of the plant species considered (Fig. 4). A comparison of the Cd and Hg adsorbed by the plants reflected differences with the soil treatment conditions and among the plants as well. Among the plant species, the differences in the Cd and Hg adsorption varied for the species Indian laburnum significantly reflected through the t-test (Fig. 5). Irrespective of the soil treatment conditions, the bioconcentration factor of the two heavy metals remained comparable with the ambient soil conditions (Fig. 6).

Although the concentration of the metals in the plants was considerably high, the significant deviation from unity (reflecting lower concentration that is present in the soil) indicates a relatively less satisfactory adsorption, particularly for Cd. Perhaps the differences in the adsorption of the two heavy metals are connected to the

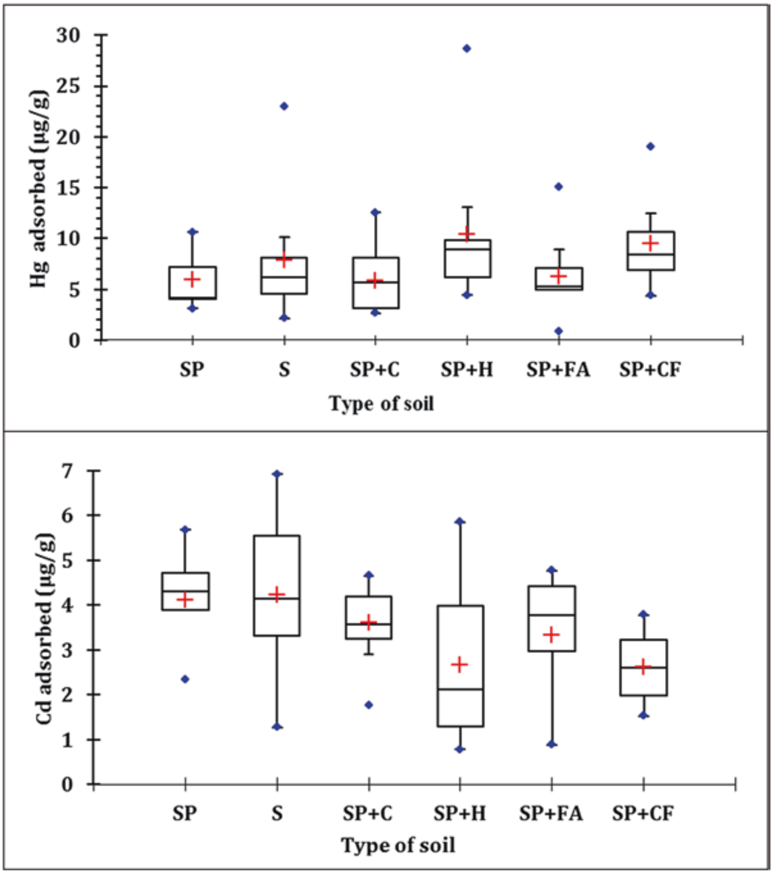


Fig. 3 Box-plot representation of the two metals (Hg and Cd) adsorbed by the plants under different soil conditions used as treatments. The variations in the soil type were used as explanatory variable for the observed differences in the metal adsorption by the plants (n = 9 replicates per soil treatment per metal)

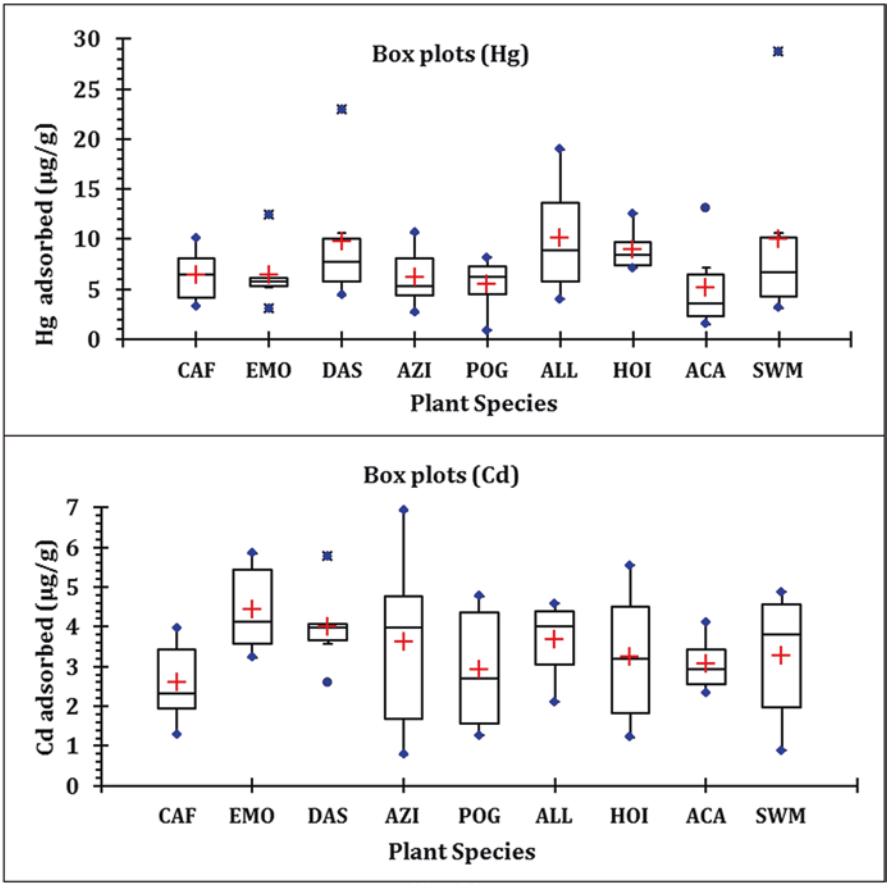


Fig. 4 Box-plot representation of the amount of the two metals (Hg and Cd) adsorbed by the nine different plant species considered in the present study (n = 6 observations per plant species per metal)

chelating system of the plants and associated physiology that are crucial in trapping the metals through the translocation process and further conversion to the plant metabolites. Alternatively, the time elapsed between the growth of the plants and corresponding metal accumulation were not synchronized for which the adsorption process may have been affected on the whole. It is apparent from the results that the plants selected for the present study are capable of changing the soil conditions from the degraded WL to a stable condition along with their growth and increase in biomass. The use of the plants for revegetation of WL implies that the establishment of the plant and subsequent growth will result in the changes in the soil conditions.

One of the bases of considering the phytoremediation process of the WL subjected to the coal extraction in the past is to reinstate the stable soil conditions both physical and chemical, using the plant species as a biological resources. In

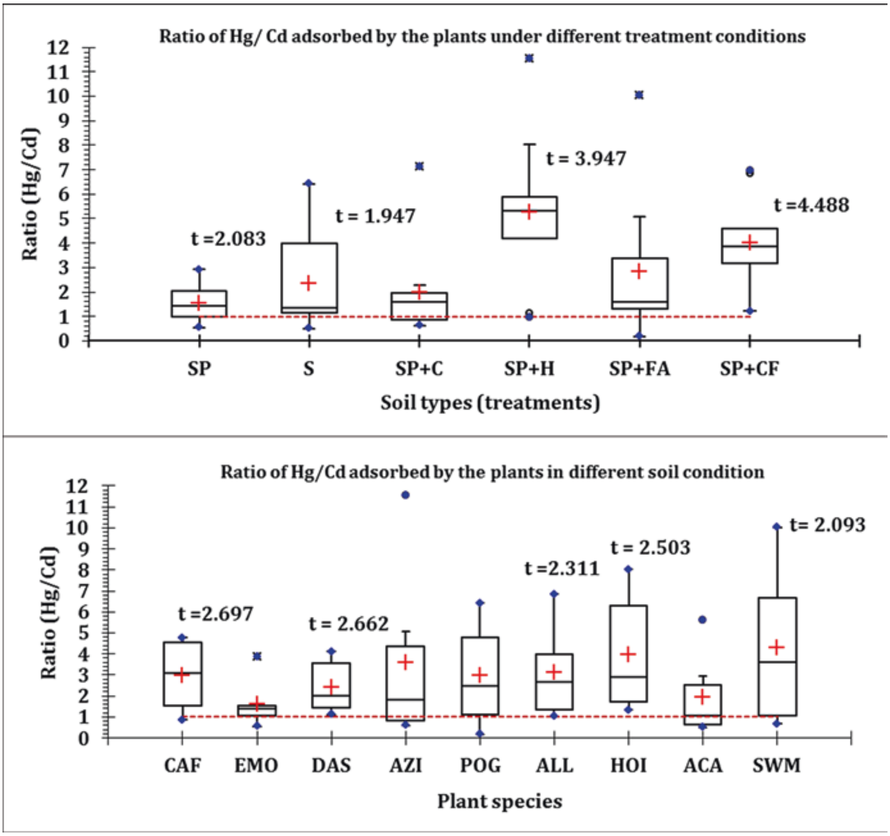


Fig. 5 The difference in adsorption of Hg and Cd by the different plant species under six different soil conditions expressed as a ratio (Hg/Cd). The reference line represents absolute similarity in the adsorption without any difference, and the values above or below the reference line represent the deviation from unity signifying the variation in the adsorption of the two metals. A one-tailed t-test was applied to justify the difference being significant or not at df = 8 for the soil treatments and at df = 5 for the plants. The significant values are marked in bold ($P < 0.05$)

terrestrial ecosystems the establishment of the plant species alters the conditions of the associated soil owing to the aggregation of the soil microbes attracted towards the plant exudates, eventually creating the rhizosphere. The rhizospheric soil is enriched with the microbes that facilitate the remodelling of the soil conditions, which further provides a positive feedback to extend the plant growth. In essence, the growth of the plants triggers the expansion of the rhizosphere followed by the changes in the soil quality parameters. As observed in the present instance, all the nine plants influenced the changes in the soil conditions along with the adsorption of the metals like Hg and Cd. Although variations in the extent of the changes in the soil conditions were obvious with reference to the initial soil conditions and the plant species, the bioaccumulation capability was an addition function that increased

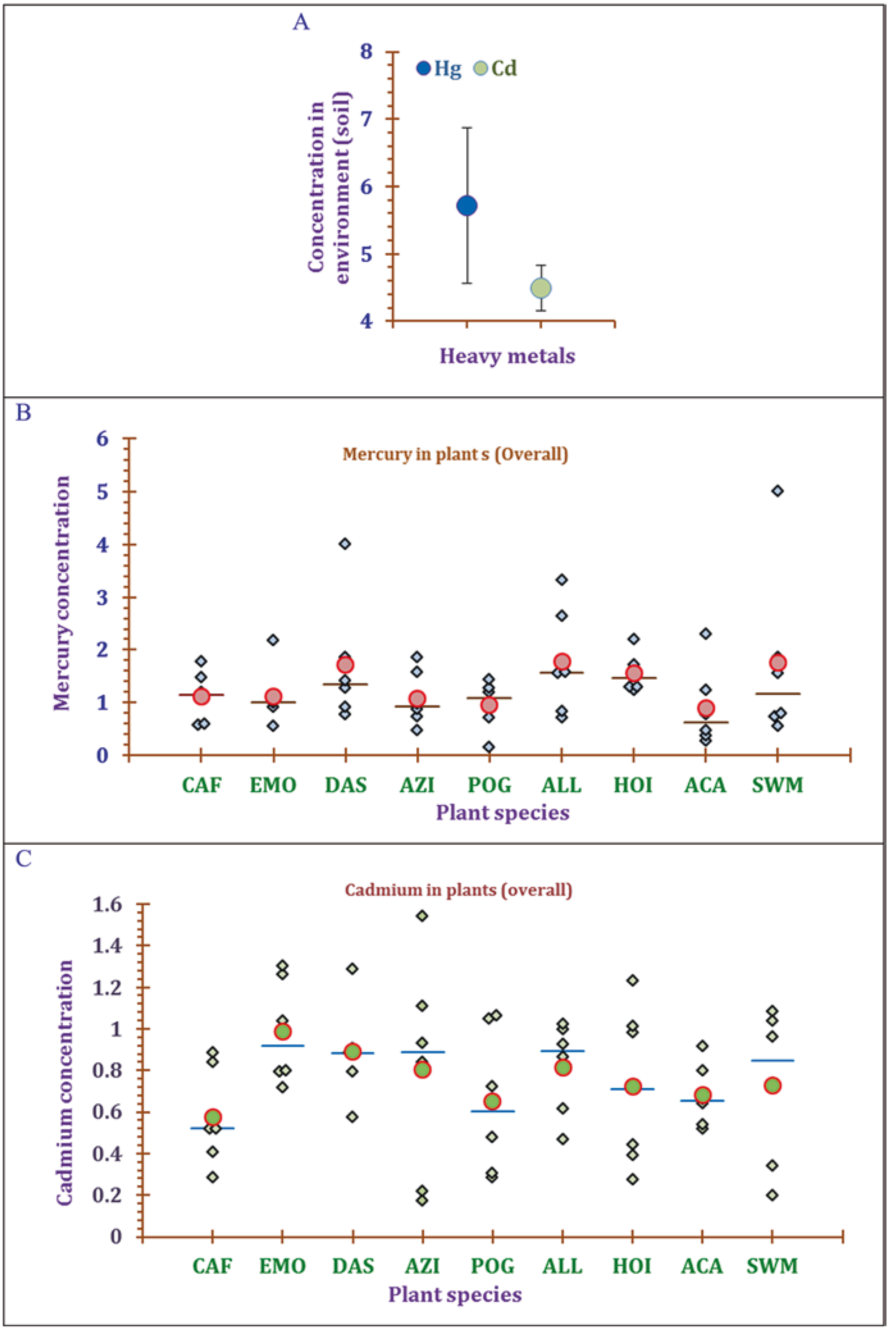


Fig. 6 The overall concentration (μg/g) of the heavy metals and Cd in soil (**a**) and the plants (**b** – Hg; **c** – Cd), irrespective of the soil treatments observed through whole tissue assay (n = 6 replicates per plant). The scatterplots in **b** and **c**, with the round filled circles, represent mean values, while the horizontal lines represent the median values for each panel (plant species)

the ecosystem services delivered by the plants. In the context of restoration of the landscape of the WL of the colliery region, the use of the plants can be considered as a suitable alternative to augment the soil conditions along with reduction in the level of the heavy metals. The success of the PR using plant species in augmented remodelling of the soil along with reduction of the heavy metals requires selection of the appropriate plant species (Pulford and Watson 2003).

Although the long generation time of the plant species defends the growth of the metal-tolerant species, the accumulation of the same enables their use in the metal-contaminated soil sites like the abandoned coal mines and allied landscapes. Bioavailability of the metals and subsequent uptake by the plants depend on several factors of the ambient soil and the existing plant species (Pulford and Watson 2003; Yadav et al. 2017). Earlier studies have shown that the plants like *Dalbergia sissoo* are able to remodel the soil and extract the heavy metals from sites containing high sulphur content in abandoned coal mine areas of Assam (Dowarah et al. 2009).

Phytostabilization and phytoextraction are highlighted as two common process of alteration of the soils of the WL of abandoned coal fields as well as other mining areas (Wong 2003). The results of the present study substantiate the selected nine plant species are capable of stabilizing the soil conditions along with the accumulation of heavy metals thereby facilitating the reinstatement of the soil to the stable conditions for further plant assemblages. In the course of demonstrating the ability of the plants Indian laburnum, Aonla, shisham, neem, siris, mahogany, etc. for the soil reclamation process, the present study substantiates the prospect of PR process aided through revegetation of abandoned coal fields. The ability of the plants in restructuring the ecological succession process is also established through their potential to grow under the diverse soil conditions mimicking the abandoned coal fields. However, the selection of the plant species should be done judiciously to reinstate the seral stages in the continuum of the succession. The changes in the soil conditions towards a favourable condition for the future community establishment may require uninterrupted time period so that the long-term benefits are achieved through revegetation and introduction of the plants in the coal field sites.

11 Restoration of Mined Wastelands: A Way Towards Sustainability

The large-scale land disturbances associated with mining operations and related concerns about the environmental effects have triggered an increasing number of rehabilitation programmes which aim for the restoration of natural ecosystems disturbed by mining. Restoration of mine sites often improves the physical and chemical characteristics of substrate and ensures the return of vegetation cover (Bradshaw 1987; Schaller 1993; Lindenmayer and Hobb 2008; Kumar et al. 2017). If specific problems hindering ecosystem redevelopment can be identified, a cure can be designed using or mimicking natural processes. According to Dobson et al. (1997), this process of identification and intervention is the essence of ecological restoration.

The most common response to land degradation has been abandonment or reliance on natural succession to restore lost soil fertility, species richness and biomass productivity (Parrotta et al. 1997; Ambasht and Ambasht 2012; Sihag et al. 2015). However, the process of natural succession on surface-mined soils is slow due to the removal of topsoil, resulting in elimination of soil seed bank and root stocks and due to soil profile disturbances (Parrotta et al. 1997; Kumar et al. 2017; Chaturvedi and Singh 2017). As many as 50 or 100 years can elapse before a satisfactory vegetation cover develops on mine waste (Bradshaw 1997). Redevelopment of advanced communities may take a millennium or more (Dobson et al. 1997).

An important goal of ecological rehabilitation is to accelerate natural successional processes so as to increase biological productivity, reduce rates of soil erosion, increase soil fertility and increase biotic control over biogeochemical fluxes within the recovering ecosystems (Parrotta 1992). Analysis of different natural successions on natural and artificial substrates suggests that one of the important factors limiting the rate of development is the process of immigration of taxa (Miles and Walton 1993; Ash et al. 1994). There are genuine difficulties in appropriate species reaching a particular site, especially if they have heavy seeds, unless they already occur in the immediate vicinity (Bradshaw 1997). Artificial revegetation is often used to facilitate the generally slow natural rehabilitation process (Bradshaw 1983; Leopold and Wali 1992). Artificial seeding of grasses and legumes or both has been a commonly used method to stabilize unconsolidated mine tailings and to encourage natural invasion of tree and shrub seedlings. This ultimately improves site fertility and moisture retention capacity (Vogel 1973). Once the abandoned mine lands have vegetation growing on the surface, the regeneration of these areas for productive use has begun, and off-site damages are minimized. In addition, establishment of the vegetation on an abandoned mine land also improves the aesthetics of the area.

Overburden is the geologic material above coal seams and below the developed soil horizons (Helm 1995). Buried seeds and rhizomes are normally absent in overburden (Singh et al. 1996). This fact makes seed reserves in the topsoil an important resource that, if handled correctly, can be used successfully to recover disturbed areas by natural vegetation (Iverson and Wali 1982; Hopkins and Graham 1983; Bellairs and Bell 1993). Since most of the soil seed reserves are found in the surface 5–10 cm (Iverson and Wali 1982; Roberts 1981; Putwain and Gillham 1990), upper 5–10 cm topsoil is recommended to be removed and replaced on the top of overburden material. However, the collection, storage and use of topsoil for restoration of mine areas are limited in many parts of the world (Noyd et al. 1997). Therefore, recent reclamation strategies have centred on creating soil that will support short-term establishment of native plant species and will sustain long-term successional development (Pfleger et al. 1994).

Harrington (1999) describes plantation-related activities used in restoration of damaged sites. According to him, the first step should be stabilization of soil surface by contours, debris dams, mulch, etc. Compaction of soil also needs to be reduced by mechanical disruption. If needed, macroporosity of the soil can be improved by incorporation of wood and shale. Soil toxicity in terms of pH, metals and salts has to be reduced by suitable amendments and plantation of resistant species and cultivars. Once suitable vegetation starts growing, herbivory and physical damage can be reduced by controlled access, fencing and trapping (Harrington 1999).

Tree Species in Reclamation of Wasteland Vast areas of land all over the world have been rendered unproductive by human activities (Choi and Wali 1995). The situation is particularly alarming in tropical areas where forest loss and degradation, as well as degradation of land of those earlier supported forests, are proceeding at unprecedented rates (Parrotta et al. 1997). Ecosystem destruction by mining for coal, quarrying for minerals and other processes to meet demands of industries is an inevitable part of civilization (Bradshaw 1983). The increasing human need for these resources will certainly accelerate further degradation of natural habitats, as most of the mining areas are on the land which was previously occupied by forests. All these will lead to acceleration of erosion of biological diversity and creation of several other environmental problems.

Plantations on MS Plantation is the oldest technology for the restoration of lands damaged by human activity (Filcheva et al. 2000; Meena and Yadav 2014; Kumar et al. 2016; Jhariya and Yadav 2018). A primary objective for achieving satisfactory rehabilitation of a mined landscape is to establish a permanent vegetation cover. There is increasing evidence that forest plantations can play a key role in harmonizing long-term forest ecosystem rehabilitation or restoration goals with near-term socioeconomic development objectives (Parrotta et al. 1997). Plantations can play a critical role in restoring productivity, ecosystem stability and biological diversity to degraded areas (Schaller 1993). Relative to unplanted sites, plantations have a marked catalytic effect on native forest development (succession) on severely degraded sites (Parrotta et al. 1997).

Numerous studies have demonstrated that land rehabilitation benefits from plantations because it allows jump-starting succession (Ang 1994; Khemnark 1994). The catalytic effects of plantations are due to changes in understorey microclimatic conditions (increased soil moisture, reduced temperature, etc.), increased vegetational-structural complexity and development of litter and humus layers that occur during the early years of plantation growth. The development of a plantation canopy can alter the understorey microclimate and the soil physical and chemical environment to facilitate recruitment, survival and growth of native forest species. Otherwise, native species would only very slowly, if ever, regenerate on degraded sites (Uhl et al. 1982; Pandey et al. 1988; Soni et al. 1989). Thus, plantations accelerate the development of genetic and biochemical diversity on degraded sites.

Plantations have an important role in protecting the soil surface from erosion and allowing the accumulation of fine particles (Bradshaw 1997). They can reverse degradation process by stabilizing soils through development of extensive root systems. Once they are established, plants increase soil organic matter (O'Connell 1986; Gill et al. 1987; Montagnini and Sancho 1990), lower soil bulk density, moderate soil pH, bring mineral nutrients to the surface and accumulate them in available form (Bradshaw 1997; Sanchez et al. 1985; Chakraborty and Chakraborty 1989; Sharma and Gupta 1989). Their root systems allow them to act as scavengers of nutrients not readily available. The plants accumulate these nutrients and redeposit them on the soil surface in organic matter, from which nutrients are much more readily available by microbial breakdown. This is exhibited in the levels of available phosphorus and potassium in afforested colliery spots (Knabe 1973).

Most importantly, some species can fix and accumulate nitrogen rapidly in sufficient quantities to provide a nitrogen capital, where none previously existed, more than adequate for normal ecosystem functioning (Bradshaw 1997). Once the soil characteristics have been restored, it is not difficult to restore a full shoot of plant species to form the required vegetation (Dobson et al. 1997). According to Faulconer et al. (1996), other advantages are that establishment of desirable tree species capable of maintaining the site will slow or prohibit invasion of less desirable weedy species, will provide economic returns in the long term, will aid in developing wildlife habitat and will promote hydrologic balance in the watershed.

Reforestation of polluted sites is part of a realistic, low-cost, ecologically sound and sustainable reclamation strategy for bringing polluted sites into productive use (Dickinson 2000). Planting trees on these sites initiates soil development and nutrient cycling and improves the aesthetic value of the site. The ecological basis through plantation for rehabilitation of damaged tropical lands has been described by Lugo (1992). Selection of appropriate plant species would be very important to ensure a self-sustainable vegetation cover. Because of deep roots, trees are able to loosen compacted soil to greater depths than grasses. The potential use of trees as a suitable vegetation cover for heavy metal-contaminated land has received increasing attention over the last 10 years (Glimmerveen 1996). Trees can maintain sustainable bionetwork through numerous processes such as maintenance of soil organic matter, rhizosphere growth and improved soil biological activity. In a given time, new self-sustaining leaf litter and litter fall will be created by trees which help in formation of humic substances (Filcheva et al. 2000).

Species Selection for Plantations The choice of plantation species is likely to greatly influence both the rate and the trajectory of rehabilitation processes (Parrotta 1992).The establishment of a permanent cover of vegetation not only involves growing plants, but it necessitates bringing into being a plant community that will maintain itself indefinitely without attention or artificial aid and support native fauna (Rodrigues 1996). Such performance could be achieved by selecting species adapted to grow, spread and reproduce under severe conditions, provided both by the nature of the dump material and the exposed situation on the dump surface (Rodrigues 1996).

The presence of certain tree species in a productive system can result in better soil structure and increased soil nutrient availability (Montagnini and Sancho 1990; Sanchez et al. 1985; Nair 1989; Young 1989). Among species that may be considered suitable for a given degraded site, there may be considerable variations in their capacity to stabilize soils, increase soil organic matter and available soil nutrients and facilitate understorey development. These variables include susceptibility to pests and diseases, patterns of aboveground and root biomass accumulation, nutrient utilization and allocation, nutrient use efficiency, nutrient re-translocation, litter production and fine root turnover, rates of litter decomposition (O'Connell 1986; Gill et al. 1987) and the presence of secondary compounds that may inhibit the activity of decomposing organisms. While most species appear to act as catalysts for ecosystem rehabilitation, broadleaf species seem to give better results than conifers (Parrotta et al. 1997). Of these, fast-growing species that represent lower successional stages should have preference, particularly those known to establish and grow well on degraded sites. In addition to their potential effects on soil fertility, species choices must be guided by seed and seedling availability, local uses for the species and economic aspects (Montagnini et al. 1995).

Trees can potentially improve soils through numerous processes, including maintenance or increase of soil organic matter, biological nitrogen fixation, uptake of nutrients from below the reach of roots of under storey herbaceous vegetation, increase water infiltration and storage, reduce loss of nutrients by erosion and leaching, improve soil physical properties, reduce soil acidity and improve soil biological activity (Filcheva et al. 2000; Buragohain et al. 2017). Given time, new self-sustaining topsoils are created by trees (Filcheva et al. 2000). However, impact of trees on soil fertility depends on their nutrient-cycling characteristics such as litter chemistry and decomposition (Montagnini et al. 1995). In addition to the nutrient sink function due to mass accumulation, some plantation species exhibit high nutrient use efficiency and may be more effective nutrient sink than the other species. In temperate environment, slower-growing, broadleaved native trees are regarded as better for amenity but less efficient for timber production (Filcheva et al. 2000). Indigenous species are preferable to exotics because they are most likely to fit into a fully functional ecosystem and to be climatically adapted (Piha et al. 1995). According to Harrington (1999), if there are native species available that are suited to the current soil and site conditions, the regeneration methods have been worked out for the desired species, and the resources are available to cover the cost, and then clearly the re-establishment of native species rather than exotics should be preferred.

12 Ecological Restoration of Mined Wasteland: Management Implication

Goals in this regard are to check further degradation; sustainable use of degraded lands; increase biomass availability along with nourishing soil; and restore ecological balance. This can be done by participatory approach with the help of local people in the planning and management of lands. Ecosystem approaches in management considering watershed would ensure integration of various ecological components (both biotic and abiotic). This would also help in enhancing the socioeconomic status of a region. Similar approaches practised in drier districts like Anantapur

(Andhra Pradesh), Tumkur, and Bangalore Rural (Karnataka) have yielded positive results with increase in land productivity and groundwater levels in the respective watersheds.

- People-friendly action programme helps local people and organizations in rehabilitating and improving the degraded lands. In this regard, management aspects are:
  - Fixing target areas (degraded forest area and pastures, public and private WL, farmlands with lower productivity).
  - Assessing the infrastructure available to meet the requirement.
  - Finding the possibilities of involving the government, NGOs and local people. The key elements of a participatory approach are local peoples' priorities; provision of secure rights and gains to the poor; flexible approaches; working with local groups and institutions; and capacity building of motivated local people.
- Government has to give priority in terms of funding, encouragement, and policy-making
- Mechanisms by which local people, NGOs and other groups can contribute to the implementation and monitoring of WL development programme on a regular basis.
- Promoting conservation of natural resources through traditional knowledge.
- Promoting ideas to consider the village as an ecosystem and to maintain its integrity.
- Providing examples of the practices done at different places.
- Integrated village ecosystem planning with watershed approach needs to be espoused for sustainable development.

This would enhance the total natural resource base by restoration and management of degraded lands, production of basic biomass needs of the village community and equity in distribution of biomass resources.

13 Phytoremediation and Restoration: Future Perspectives

The remediation of soil that is heavily contaminated due to coal or metal mining involves excavation, removal of soil to secured land fields and filling of topsoil, which is expensive and requires site restoration. Alternatively, the contaminated soil may be dealt with bioremediation or PR, which is the use of plants or other biological measures to remove, destroy or sequester hazardous substances from the soil and waste piles (Ojuederie and Babalola 2017). An account of specific plant species that have been used to combat different types of soil pollution has been given by Prasad (2004). However, restoration of mine waste piles depends on the substrate characteristics and ability of the plant species to proliferate in the substratum.

Due to the extreme consequences, environmental contamination with heavy metals, particularly lead and Hg, is a significant concern. Now faced with these overly extensive environmental problems, a cost-effective means of remediation pertinent to the contaminated areas must be found. There are a number of conventional remediation technologies which are employed to remediate environmental contamination with heavy metals such as solidification, soil washing and permeable barriers. But a majority of these technologies are costly to implement and cause further disturbance to the already damaged environment. PR is evolving as a cost-effective alternative to high-energy, high-cost conventional methods. It is considered to be a "Green Revolution" in the field of innovative cleanup technologies (Henry 2000).

PR of mine land offers a great challenge, to restore its productivity and fertility and also to re-establish the ecological cycles in the rhizosphere with identification of suitable plant species and also the amendment of some suitable blending material on such degraded land. It is one of the widely used emerging techniques for soil remediation, to remove pollutants from the environment or to stabilize them (Salt et al. 1998). Conventional PR techniques mostly involve growing plants, to remove pollutants or to stabilize the contaminated site. But long-term sustainability on coal MS dumps requires a scientific approach. Selective microorganism's inoculation at such sites increases the better survivability, growth and biomass of the plants. PR of the coal MS dumps therefore needs an integrated biotechnological approach, which includes blending of spoil with organic waste and inoculation with biofertilizers and mycorrhizal fungi to achieve revegetation and restoration of fertility of these dumps.

PR does not require expensive equipment or highly specialized personnel, and it is relatively easy to implement. It is capable of permanently treating a wide range of contaminants in a wide range of environments. However, the greatest advantage of PR is its low cost compared to conventional cleanup technologies (Raskin and Ensley 2000; United States Environmental Protection Agency 2000). The most important challenge is to improve the efficiency of phytotechnologies depending upon dissemination of results, risk assessment, public awareness and acceptance of this green technology, as well as the promotion of networking between scientists, industrials, stakeholders, end users, non-governmental organizations and governmental authorities which are major issues that must be tackled to ensure that PR programmes are implemented successfully.

14 Conclusion

In view of ecological restoration of coal mine WL, the present study explored the vegetation pattern and the soil quality, using Raniganj Colliery, West Bengal, India, as a model geographical area. The objective of the study was to highlight the ecosystem conditions of the WL using the vegetation pattern and the soil quality as surrogates. Evaluation of the growth pattern of nine different plant species against six different soil conditions was made to highlight the prospective use in enhanced vegetation of the WL to restore the seral stages in successional continuum. Plant growth induces changes in the soil conditions following the generalized assembly rules of the community organization, which was also assessed for the selected plants along with the ability to bioaccumulate the heavy metals from the ambient soil. The information on the plant species assemblages and the soil quality provided a basis to comment on the prospect of the ecorestoration of the WL following the principles of PR.

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