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Forest Dynamics and Conservation

Science, Innovations and Policies

Springer

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Foreword

Disturbances in forested landscapes play a fundamental role in forest dynamics and diverse ecosystem services to be produced. Anticipated scenarios of global change and increasing human-induced interferences have projected relevant alterations in forest dynamics globally. Since 1990, deforestation and degradation at alarming rates have resulted in the loss of more than 420 million hectares of forest. Agriculture intensification has been the mega driver of deforestation, forest degradation, and loss of forest biodiversity in the *Anthropocene*. Current negative trends of deforestation and degradation will further destabilize progress towards climate, restoration, land degradation neutrality, and sustainable development goals. Transformative changes are required to be mainstreamed to manage the existing forests and conserve forest biodiversity. Understanding the drivers of deforestation and forest degradation is critical to ensure responsive, effective, and efficient forest management approaches to reduce and halt deforestation, forest degradation, and halt climate outcomes. Interactive governance and community engagement to sustainably manage the forest ecosystems is a relevant transformative approach that can improve the community and ecosystem resilience and, ultimately sustain forest resources.

This book not only explores the benefits and challenges of Forest Dynamics and Conservation in the *Anthropocene*, but also explores the different advances in science, innovations, and policies that can be implemented like the social dimension of forestry, long-term ecological monitoring, advanced mapping, modelling tools, deep learning neural network, biophysical indices, REDD+, PES, and agroforestry for landscape restoration to monitor and implement them. Different chapters providing insights to innovations followed by advanced institutional provisions and governance frameworks are proposed for the conservation of forest ecosystems in the changing and warming world. For example, public interests and private incentives in designing an ecological payment system presents a unique approach by creating market-based mechanisms for environmental protection and appears to be a good choice to steer public policies and private behaviour towards more sustainable management systems of natural resources. Similarly, the Emission Reductions Programme for addressing drivers of deforestation and forest degradation has the potential to address the drivers of emissions-causing deforestation and forest degradation and enhance forest carbon stock, ultimately paving the way for results-based payments for future emissions reductions. The different innovative approaches presented in this book provide an opportunity to replicate them in diverse forest types, ecosystems, settings with some adjustments if needed.

Recent innovations in mapping invasive species in forest areas, groundwater-dependent ecosystems, forest soil ecosystems, South Asian Nitrogen Hub, urban forests, forest fires, ecotourism, and their relevance in forest conservation have found a special place in this book. Starting from the drivers of deforestation and forest degradation to the gender agenda of community forests at risk to plant–herbivores interactions in the forest ecosystem, the implication of the social dimension of forestry to forest management has been discussed. The book initiates new discussions on diverse mapping and modelling tools and research methods in sustainable forest management. Likewise, case studies on the importance of REDD+, PES, and Ammonia Nitrogen Hub demonstrate the need to develop local and subnational pilots for application and research for mainstreaming them in forest policies.

Considering the complexities and uncertainties linked with climate change and its impact on diverse forest ecosystems, it is timely and important to explore diverse approaches and interventions for a sustainable forest future, as this book has done. It not only quantifies and explores the importance of forest dynamics, but also suggests diverse science, innovations, and governance approaches for ensuring forest conservation which will eventually help in localizing many global goals and targets. Academicians, researchers, forest managers, bureaucrats, conservationists, policy planners, governmental and non-governmental agencies will find this book helpful as the book delivers an integrated knowledge on forest dynamics and conservation and makes a valuable contribution towards building a sustainable and resilient urban future.

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Abbreviations

%	Percent
ABM	Agent-based model
ADAS	Atmospheric data assimilation system
AEPC	Alternative Energy Promotion Centre
AFM	Adaptive forest management
AI	Artificial intelligence
ALS	Airborne laser scanning
AM	Adaptive management
AMSL	Above mean sea level
ANCSA	Alaska Native Claims Settlement Act
ANN	Artificial neural network
AOD	Aerosol optical density
AOI	Area of interest
APAR	Absorbed photosynthetically active radiation
ARCGIS	Aeronautical Reconnaissance Coverage Geographic Information System
ARIES	Artificial intelligence for ecosystem services
ASL	Above sea level
ASTER	Advanced Spaceborne Thermal Emission and Reflection
AUC	Area under curve
AVHRR	Advanced very high-resolution radiometer
BBP	Bannerghatta Biological Park
BDA	Bangalore Development Authority
BEF	Biodiversity and Ecosystem Functioning
BI	Brightness index
BMRDA	Bangalore Metropolitan Region Development Authority
BNHS	Bombay Natural History Society
BNP	Bannerghatta National Park
BOD	Biological oxygen demand
BOM	Bureau of meteorology
BRT	Boosted regression trees
C	Carbon
C/N	Carbon-to-Nitrogen ratio

Ca^{+2}	Calcium
CART	Classification and regression trees
CBD	Convention on Biological Diversity
CBFM	Community-based forest management
CDF	Cumulative density function
CES	Compensation for environmental services
CF	Community forestry
CFC	Community forest certificate
CFM	Collaborative forest management
CFMC	Community Forest Management Committee
CFUG	Community Forest User Group
CI	Colour index
CIS	Center for Sociological Research
CNN	Convolutional neural network
CO_2	Carbon dioxide
COP	Conference of the Parties
CPCB	Central Pollution Control Board
CRS	Coordinate reference system
CSR	Corporate social responsibility
CSS	Centrally sponsored schemes
Cu	Copper
CVM	Contingent valuation methodology
CWA	Clean Water Act
CWC	Canopy water content
CWD	Coarse woody debris
Dbh/DBH	Diameter at breast height
DFDE	Database on Forest Disturbances in Europe
DGVM	Dynamic Global Vegetation Model
DID	Department of irrigation and drainage
DL	Deep learning
DO	Dissolved oxygen
DOAS	Differential optical absorption spectroscopy
DS	Data science
DSS	Decision support system
EC	Electrical conductivity
EC	Eddy-covariance
EES	Ecological-Economic-Social Systems
EFG	Ecosystem functional groups
EFI	European Forest Institute
EFN	Extrafloral Nectaries
EM	Empirical model
ER	Emission reductions
ERPA	Emission Reductions Payment Agreement
ERPD	Emission Reductions Program Document

ER Program	Emission Reductions Program
ES	Ecosystem services
ESA	European Space Agency
ESA	Endangered Species Act
ESZ	Eco-sensitive zone
ETg	Evapotranspiration
EVI	Enhanced vegetation index
FAO	Food and Agriculture Organization
FC	Faecal Coliform
FC	Fully connected layers
FCN	Fully Convolution Network
FCPF	Forest Carbon Partnership Facility
FD	Forest Department
Fe	Iron
FECOFUN	The Federation of Community Forestry Users Nepal
FEES	Forest Ecological-Economic-Social Systems
FESB	Forest Ecosystem Services and Benefits
FI	Forest informatics
FIA	Forest inventory and analysis
FM	Forestry map
FNP	Forestry National Plan
FPTF	Forest products trade flow database
FRA	Forest Rights Act
FRA	Forest resources assessment
FS	Faecal Streptococci
FS	Forestry statistics
FUA	Forest Users Associations
FVC	Fraction vegetation cover
FVI	Fractional vegetation index
G	Genotype
GBH	Girth at breast height
GBIF	Global biodiversity information facility
GBM	Gradient boosting machine
GCMs	General circulation models
GCRF	Global Challenge Research Fund
GDD	Growing degree days
GDEs	Groundwater dependent ecosystems
GDV	Groundwater-dependent vegetation
GEF	Global environmental facility
GEOS-5	Goddard Earth Observing System Model, Version 5
GETP	Ghana Economic Transformation Project
GFW	Global forest watch
GHG	Greenhouse gases
GIS	Geographic information system
GLM	Generalized linear model

GMTC	Geographic mosaic theory of coevolution
GOK	Government of Karnataka
GoN	Government of Nepal
GP	Gangetic Plains
GPP	Gross primary production
GPS	Global positioning system
GPU	Graphics processing unit
GW	Groundwater
H	Hydrogen
HEC	Human-Elephant Conflict
HIMAWANTI	The Himalayan Grassroots Women's Natural Resource Management Association
HM	Hybrid model
HMLS	Hand-held mobile laser scanning
IaaS	Infrastructure as a Service
IAM	Integrated Agricultural Model
IDA	International Development Agency
IDR	Indonesian Rupiah
IGP	Indo Gangetic Plain
ILTER	International Long-Term Ecological Research
INMS	International Nitrogen Management System
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IRS	Indian Remote Sensing Satellite
IT	Information technology
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
J-C hypothesis	Janzen-Connell hypothesis
K^+	Potassium
KFD	Karnataka Forest Department
kNN	k-Nearest Neighbour
LADA	Langkawi Development Authority
LAI	Leaf area index
LF	Leasehold forestry
LFFs	Large forest fires
LiDAR	Light detection and ranging
LISS	Linear imaging self-scanning system
LPG	Liquefied petroleum gas
LTEO	Long-Term Ecological Observatories
LTER	Long-Term Ecological Research
LTFRA	Long-Term Forest Resources Assessment Database
LULC	Land use land cover

LULCC	Land use and land cover changes
LUT	Look up table
MaxEnt	Maximum entropy
MCDM	Multi-criteria decision-making
MCGM	Municipal Corporation of Greater Mumbai
MEA	Millennium Ecosystem Assessment
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
Mg^{+2}	Magnesium
MICE	Meetings, incentives, conferences and exhibitions
MIMES	Multi-scale integrated models of ecosystem services
ML	Machine learning
MLA	Machine learning algorithms
MLS	Mobile laser scanning
MMR	Mumbai Metropolitan Region
Mn	Manganese
Mo	Molybdenum
MODIS	Moderate resolution imaging spectroradiometer
MoEFCC	Ministry of environment, forest and climate change
MOTAC	Ministry of Tourism, Arts and Culture
MRV	Monitoring, reporting and verification
N	Nitrogen
Na^+	Sodium
NbS	Nature-based solutions
NCPs	Nature's contributions to people
NDCs	Nationally determined goals
NDVI	Normalized difference vegetation index
NGOs	Non-Governmental Organizations
NH_3	Ammonia
NIR	Near infrared
NLCP	National Lake Conservation Plan
NO_2	Nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NPP	Net primary production
NRCD	National River Conservation Division
NRCP	National River Conservation Plan
NTFPs	Non-timber forest products
NWC	National Water Commission
NWCP	National Wetland Conservation Programme
NWI	National Water Initiative
O	Oxygen
OECD	Organization for Economic Cooperation and Development
OLAP	Online analytical processing
OMI	Ozone monitoring instrument
OV	Option value proper

P	Phosphorus
PA	Protected area
PaaS	Platform as a Service
PBM	Process-based model
PES	Payment of ecosystem services
PFES	Payment for forest environmental services
PFT	Plant functional type
pH	potential of hydrogen
PHU	Peatland hydrological unit
PLS	Personal laser scanning
PNC	Penarak Nature Centre
ppm	Parts per million
PSSRa	Pigment Specific Simple Ratio a (chlorophyll index)
PUA	Pasture Users Associations
QOV	Quasi option value
QUT	Queensland University of Technology
RDBMS	Relational database management system
RECOFTC	Regional Community Forestry Training Center for Asia and the Pacific
REDD IC	REDD Implementation Centre
REDD+	Reducing emissions from deforestation and forest degradation in developing countries
REIP	Red-edge inflection point
RES	Rewards for environmental services
RF	Random forest
RFA	Recorded forest area
RGB	Red green and blue
RMP	Revised master plan
ROIs	Real options in a project
ROOs	Real options on a project
RS	Remote sensing
RUM	Random utility model
S	Salinity
SaaS	Software as a service
SANH	South Asia Nitrogen Hub
SAR	Synthetic Aperture Radar
SAVI	Soil-adjusted vegetation index
SD	Sustainable development
SDGs	Sustainable development goals
SDM	Species distribution modelling
S-DSS	Spatial decision support system
SES	Socio-ecological system
SFM	Sustainable forest management
SGNP	Sanjay Gandhi National Park
SNAP	Sentinel application platform

SNI compost	Indonesia National Standard of Compost
SOC	Soil organic carbon
SPCB	State Pollution Control Board
Spp.	Species (plural)
SQL	Structured query language
SSFM	Synergetic sustainable forest management
SVM	Support vector machines
T	Temperature
TAL	Terai Arc Landscape
TC	Total Coliform
TDS	Total dissolved solid
TEV	Total economic value
TLS	Terrestrial laser scanning
TM	Thematic mapper
TOF	Trees outside forests
UAVs	Unmanned aerial vehicles
UGGG	UNESCO Global Geopark Gazette
UKRI	United Kingdom Research and Innovation
UN FAO	Food and Agricultural Organization of the United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UN-SDGs	United Nations-Sustainable Development Goals
UPM	Universiti Putra Malaysia
USLE	Universal Soil Loss Equation
WTA	Willingness to accept
WTP	Willingness to pay
WV II	World View II (Satellite Data)
WWF	World Wildlife Fund
ZAK	Zoo Authority of Karnataka

1 Protecting Forest Structure and Functions for Resilience and Sustainability Concerns in the Changing World

Manoj Kumar, Shalini Dhyani, and Naveen Kalra

Abstract

Forest ecosystems are one of the most important ecosystems on earth, and sustainability of the planet heavily relies on diverse ecosystem services emerging from them. In order to maintain unrestricted flow of ecosystem services in the warming world, it is essential to conserve and sustainably manage them. This necessitates an understanding of past, present, and future structural and functional pattern of forests, their functioning as well as health status. There are substantial indications that unsustainable human activities have significantly affected the structure and functioning of natural forest ecosystems. To explain the distribution of forests, their functioning, and different drivers of loss to which forests are exposed, enormous methodological and socio-ecological and governance advancements have already taken place. In the opening chapter, we elaborate on the understanding of forest ecosystems from variations in definitions and conceptualizations of forests, emerging challenges, monitoring advancements, etc. Chapter broadly covers scientific advancements for monitoring various stressors, forest degradation, inventory using advanced tools to present the fate of forest structure, and functioning in the changing world. The volume highlights drivers of deforestation and forest degradation, provides insights to innovations, and also touches advanced institutional provisions and governance framework.

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The thematic and cross cutting chapters bring in scientific evidence-supported information and solutions to enhance the prospects for conserving forests in the fast changing world. Apart from providing a broader overview of the book, its growing relevance, the chapter also offers a brief outline of the chapters in different sections of the book.

Keywords

Forest monitoring · Forest management · Deforestation · Ecosystem services · Climate change

1.1 Introduction

Well-being of society and the human consumption of natural resources depend on available diverse biodiversity elements and ecosystem services. Structure and function of ecosystems interact in immensely complex spatial patterns from local to global levels to provide diverse nature's contributions for well-being (Mirtl et al. 2018). Our planet is covered with diverse ecosystems, and forest is one of the important ones. The Global Forest Resource Assessment (FRA) by the FAO at an interval of 5 years reveals that the total forest area in the world stands at 4.06 billion hectares, i.e., 31% of the land area (FAO 2020b). The spatial distribution patterns of forest ecosystems are determined by its relation with diverse environmental and climatic parameters that helps in determining the structure of the forest ecosystems in specific biogeographic zones. The diversity exhibited by the forests in terms of structure and function leads to the concept of forest types (Muys 2021). More than 850 million people across the world live close to natural forest ecosystems, whereas approximately 350 million are directly dependent on them for their livelihoods and other subsistence requirements (Runyan and Stehm 2020). Forests are home to rich floral, faunal, and organisms and by regulating global biogeochemical cycles, and supporting diverse subsistence demands and livelihoods, forests have been widely acknowledged for their role in securing human well-being (Kumar et al. 2019a; Haq et al. 2020). Forest biodiversity is key resource for many crucial ecosystem services, contributions, and impact of biodiversity on ecosystem functioning and processes (BEF) has central to ongoing ecosystem and biodiversity research (Pan et al. 2018). The inherent ability of the natural forests to recover after disturbances, i.e., their resilience, regulates their capacity to support its functions and process over time (Ibáñez et al. 2019). Ecosystem resilience as a vital component for sustainable human development and sustainable use of forest resources is relevant to uphold the sustainable consumption patterns by diverse socio-economic systems (Yan et al. 2011). Forests have been historically connected with human well-being for their diverse benefits, but it is relevant to acknowledge that the capacity to support human well-being is not unlimited and they are under significant stress because of much ongoing natural and human-induced pressure (Anonymous 2018). Forest structure and functioning have been significantly linked to the type and extent of human dependency (Haq et al. 2021). This is further influenced by the socio-economic and biophysical factors that lead to forest loss (Gardner et al. 2010). Forests have emerged as one of the most threatened ecosystems because of increasing deforestation and degradation trends because of the diverse direct and indirect drivers of forest loss (Li and Jiang 2021). Forest biodiversity that is affected by diverse range of drivers of loss that includes changes and human-induced land use land cover changes in various production systems is one of the relevant drivers worldwide (Díaz et al. 2019). The United Nations Framework Convention on Climate Change (UNFCCC) and independent nations in various scientific and international strategic alliances have stressed on the unforeseen and irreversible impacts of climate change on rich but fragile natural forest ecosystems. The structure and functions of forest ecosystems are rapidly changing due to forest fires (Joshi et al. 2021), deforestation (Runyan and Stehm 2020), urbanization (Olokeogun and Kumar 2020), climate change, and other relevant natural and anthropogenic drivers (Kumar et al. 2019b; Molina and Abadal 2021). In less than last 100 years, world has already lost forests equivalent to the loss in the last 9000 years. Global deforestation peaked around early 80s with a loss of around 150 million hectares during that decade (Ritchie and Roser 2021). However, the rate of loss has shown a considerable decline from 5.2 million ha/annum from 2000 to 2010 to 4.7 million ha/annum from 2010 to 2020. Furthermore, the rate of deforestation has also decreased from 12 million ha/annum from 2010 to 2015 to 10 million ha from 2015 to 2020 (FAO 2020b). Constant decline in forest cover in the past 50 year has reduced the ability of nature to ensure and support human well-being (Brauman et al. 2020). This decline, the way it is continued unrestricted, is expected to also affect the achievement and localization of the 2030 Agenda of UN SDGs and many other relevant global targets (Managi et al. 2019).

For centuries, forests have been considered climate stabilizers as they can significantly support cost-effective diverse nature-based climate solutions to more than 30% climate mitigation strategies to reduce vulnerability due to climate change and achieve globally projected UNFCCC targets (Brandon 2014; Griscom et al. 2017). There is growing demand to understand ecosystems as a critical components of the biological diversity of the planet in the changing world and as crucial natural capital that sustains human well-being (Ekins 2003). In a rapidly changing world where catastrophic climatic threats, land degradation, water depletion, industrialization, and pollution-related issues are frequent and prevalent, understanding the changing face of forest ecosystems is essential. For forest ecosystems to be considered biodiverse, it is necessary to evaluate soil, water, plant, and atmospheric intercontinuum systems in light of spatio-temporal variations. Comprehensive understanding of ecological processes is necessary to understand the changing patterns in the natural forest ecosystems (Kumar et al. 2020a; Muys 2021). For the preservation of natural forest ecosystems, a better understanding of critical socio-ecological interdependencies such as subsistence requirements of local communities, traditional agroforestry ecosystems, rapid land use, and land cover change dynamics, will be relevant (Dhyani and Dhyani 2020; Savita et al. 2018; Kumar et al. 2020b, 2021a). There is global evidence that forests develop differently under different production environments (Peng 2000; Kumar et al. 2018). There is necessity to address major changing dimension of forests through relevant forestry research to leverage upon the available data, knowledge, tools, approach to understand the fate of forests in the changing world and identify opportunities to improve the existing situations (Kalra and Kumar 2018; Rawat et al. 2020).

The pace of degradation of nature's contributions from forests makes their effective management crucial in present and future. Management of the forest ecosystem needs to be planned ahead of time and visionary in nature, as it takes years to replenish the supply of diverse ecosystems goods and services (FAO 2020b). Short- and long-term socio-ecological interactions with forests that aid in the provision of direct use values should be part of forest management strategies including socio-cultural, socio-ecological, and economic contributions (Dhyani et al. 2021). Depending on the amount of forest degradation, site-specific climate-adaptive restoration (Dhyani et al. 2020a) interventions are required to reduce dependency of local communities on forest resources to reinstate their necessary functions for long-term human well-being. There is growing need to re-examine our current approaches and discover customized metrics based on contemporary technologies, artificial intelligence, and big data that are well supported by indigenous and local knowledge systems enhance outcomes from conservation and restoration projects (Dhyani et al. 2020a).

Opening chapter for this volume presents overview about the present state of knowledge related to forests and sustainability of forests. Chapters in this book are authored by invited expert professionals, scientists, and practitioners who have decades of research experience on diverse research aspects of forest ecosystems. These experts have contributed innovative approaches to improve existing forest research to reduce deforestation and forest degradation, improve socio-ecological and economic benefits, and enhance climate adaptations for human well-being. The edited book volume is an effort to showcase the context, concept, issues, cases, relevance, and growing need to mainstream innovations in forestry research and governance in decision making. Despite forests across the world facing threat from extractions and climate variabilities, vulnerabilities importance of scientific and socio-ecological and economic innovations in forestry research are either ignored or have not received sufficient recognition so far. Under the different subheadings of this opening chapter of this book, we not only bring the diverse conceptualization of forest ecosystems but also showcase ongoing developments and novel approaches for enhancing mapping, scenario assessment, and sustainable management of natural forest ecosystems. Chapters in different sections of this book volume provide a broader overview on scientific advances in the field of forestry research followed by the key gaps and issues to be addressed. A dedicated last section of the book volume discusses about the opportunities and pathways to mainstream sustainable socio-ecological and economic approaches in forest policies planning.

1.2 Conceptualizing "Forest"

The definition of "forest" differs in diverse perspectives, management strategies, and assessment studies (Chazdon et al. 2016). Nearly 1600 distinct definitions of "forest" have been developed across the world, for a specific purpose in academia, research, or policies (Lund 2014). The multiple ways in which a forest has been defined show the humungous diversity which exists in forest definitions, conceptualizing forests, forest types, and other biogeographic zones around the world. A specific definition might leave out diverse forest types such as mangroves or alpines, a broader definition might lead to loopholes for misuse whereas, a definition that is only relevant to local environment might be rendered meaningless for global use (UNEP 2009). The Food and Agricultural Organization (FAO) regards forest as a land which is spread in more than 0.5 ha in size and is covered with trees of height greater than 5 m (FAO 2020a). The International Union for Conservation of Nature (IUCN) has considered forest as a "land having presence of continuous stand of trees" (IUCN 2012). Globally, international organizations and conventions have agreed on a few universal definitions, which are presented in Table 1.1.

Canopy cover and land use are the most commonly used criteria for defining a forest. The definitions by UNFCCC and FAO are based on parameters *viz.,* minimum area, minimum height, crown cover percentage, temporary and/or strip width (Trines 2002).

Table 1.1 Diverse concepts and definition for forest ecosystems as proposed by different international organizations

Proposed by	Definition of forest
UNFCCC (2001)	"Forest is a minimum area of land of 0.05–1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10–30 percent with trees with the potential to reach a minimum height of 2–5 meters at maturity in situ." "A forest may consist either of closed forest formations where trees of various storey and undergrowth cover a high proportion of the ground or open forest. Young natural stands and all plantations which have yet to reach a crown density of 10–30 percent or tree height of 2–5 meters are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention such as harvesting or natural causes, but which are expected to revert to forest."
UN FAO FRA 2020 (FAO 2020a)	"Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use."
UN CBD	"Forest is a land area of more than 0.5 ha, with a tree canopy cover of more than 10%, which is not primarily under agricultural or other specific non-forest land use."

1.2.1 Forest Types and Structure

A forest type is essentially a unit of vegetation which exhibits broad characteristics in terms of physiognomy and structure. The characteristics exhibited by a single unit of forest are adequately pronounced for its distinction from other such units. The vegetation characteristics of a particular region are largely dependent on the climatic conditions (temperature, precipitation, etc.) of the region which functions in isolation and in combination with the nature of the soil (Champion and Seth 1968). On a global scale, FAO classifies forests based on the climatic domain that the forest occupies namely Boreal, Temperate, Subtropical, and Tropical forests. With the purpose to maintain a standardized nomenclature for the understanding of forest types across the globe, IUCN has presented a habitat classification scheme classifying forests into nine broad types, according to their climatic zone and ecological characteristics viz., Boreal, Subarctic, Subantarctic, Temperate, Subtropical/tropical dry, Subtropical/tropical moist lowland, Subtropical/tropical mangrove vegetation above high tide level, Subtropical/tropical swamp, Subtropical/tropical moist montane, etc. (IUCN 2012). The classification of forests on a global scale is a direct function of the dynamism that all processes portray. Furthermore, these forests are already facing the impending risk of collapse (Sato and Lindenmayer 2018). IUCN has recently proposed a Global Ecosystem Typology which is a hierarchical classification system aimed at classifying ecosystems wherein the upper levels would define the ecosystem by their ecological functions, and the lower levels would distinguish the ecosystem based on their species assemblages (Capotorti et al. 2020). This classification system involves the classification of the globe into five realms, subsequently into 25 biomes, and into Ecosystem Functional Groups (EFG) in the first three levels. Through the EFGs, the presence of ten categories of forests that fall in the broader domains of tropical-subtropical forests and temperate-boreal forests and woodlands are identified. The innovativeness in this concept lies in its capability to represent the duality that is exhibited by an ecosystem in terms of composition and functionality that helps in identification of ecosystems that are in a precarious state and require immediate conservation and protection considerations (Keith et al. 2020). While forest types give us an idea about the diversity of forests spatially, it does not inform us about the density or the health of the forest. The density of the forest can be understood through the forest cover statistics. The term "forest cover" is associated with the terrestrial ecosystems which refer to the area of land covered by forests. Amongst forest types, proportionally, the tropical forests cover the largest area on the planet at 45% (FAO 2020b).

1.3 Forests Support in Diverse Nature's Contributions

Recently, natural capital has invited interest of researchers and policy planners to support and endorse sustainability (Kumagai et al. 2021). In his capability approach, Amartya Sen defines capabilities as the means of maintaining livelihood as well as intangible elements for achieving overall human well-being (Fritz-Vietta 2016).

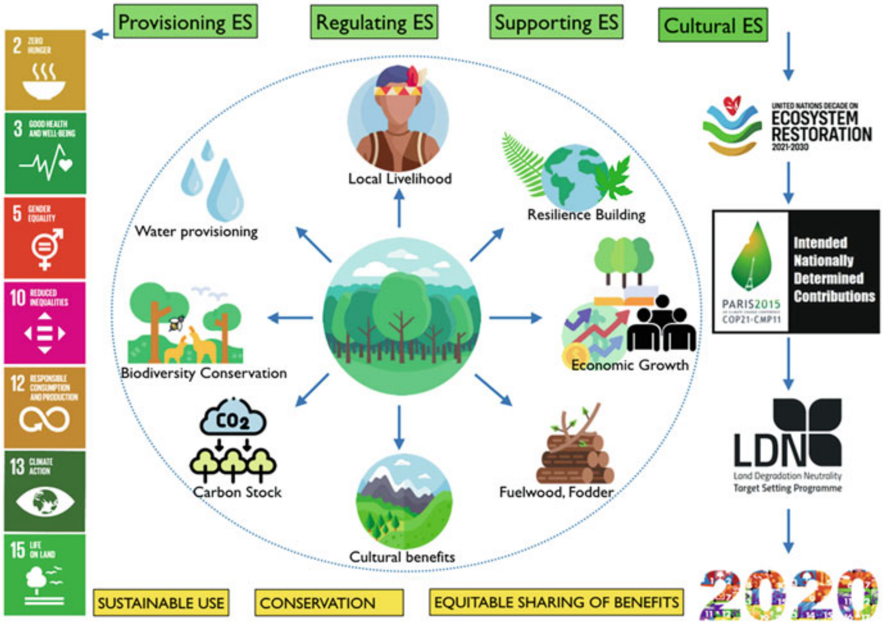

Fig. 1.1 Diverse ecosystem services (NCPs) harnessed from natural forest ecosystems and their role in localizing and realizing diverse global goals and targets

Forest ecosystem is source of innumerous provisioning benefits, diverse regulating, supporting as well as cultural benefits (Dhyani and Dhyani 2016, 2020; Dasgupta et al. 2021; Kadaverugu et al. 2021) (Fig. 1.1). These benefits and functional roles have been represented as ecosystem services (ES) by Costanza and also highlighted in Millennium Ecosystem Assessment (MEA 2005; Costanza et al. 1997). Intergovernmental panel on biodiversity and ecosystem services (IPBES) has replaced the "ecosystem services" term with a more advanced "nature's contributions to people" (NCPs) (Kenter 2018). Origin of NCPs from the IPBES conceptual framework has a transdisciplinary approach that is action-oriented, and has inclusiveness to support and include pluralism. NCPs recognize diverse and emerging culturally mediated ideas about nature's contributions to people and what can be co-produce along with, nature (Hill et al. 2021). NCP is not very different from previously carried out ES research, but includes five relevant conceptual concepts about the NCP that include diverse worldviews about NCP, context-specific perspectives about NCPs, relational values of nature, diverse reporting categories, and inclusive language that provides novel conceptualization of nature-people relations and connections (Kadykalo et al. 2019). The differences between the instrumental and intrinsic values of nature and NCP indicate the broader array of the benefits people can harness from the natural forest ecosystems (Fritz-Vietta 2016). There was subsequently, emergence of a new concept known as ecosystem dis-services that reflect to the functions that harm or affect human well-being (Sandbrook and Burgess 2015; Costanza et al. 2017).

Spread of zoonotics, resulting in diseases and/or pandemics, is considered a significant disbenefit if the nature was degraded, and unsustainably used (Morand and Lajaunie 2021). The provision of diverse classes of ES or NCP largely depends on the process and functions of terrestrial biodiversity and complex biogeochemical cycling in the forest ecosystems. These relevant natural biogeochemical cycles operate at different spatio-temporal scales and rates. For millennia, humans have been harnessing the larger benefits of biogeochemical cycles for their well-being by living in harmony with the nature. In recent times, most of the ecosystems are been largely shaped by human interventions and interferences. Accidentally or by their interventions, they have a significant control over all kinds of ecosystems. This control has expanded and affected ES and NCPs that support human well-being, leading to global decline in the quality of NCPs (Kotiaho and Halme 2018).

1.3.1 Valuation and Mapping of NCPs from Forests

Valuation of NCPs can help decision-making process for sustainable management of natural resources. Economic valuations for NCPs include diverse factors viz., forest, as well as agricultural land, livestock rearing, fisheries, ores, and fossil fuels (Islam and Managi 2021). Valuation of NCPs helps to identify the critical ecosystem services from rich ecosystems and understanding the spatial distribution of these services by including them with endemism for emerging risks due to anthropogenic pressure for developing conservation policies in priority areas (Crossman et al. 2013). However, multifunctionality of ecosystems and their complex structure and functions are involved in diverse ecosystem services that pose a challenge for quantifying and valuation of ES that involves historical and spatial mapping, quantification, and simulations approaches (Birkhofer et al. 2015). In last few decades, valuation of ecosystem services has received considerable attention in ecosystem research and policy planning (Ninan and Inoue 2013). In 2011, forest sector contributed approximately 0.9% of the global GDP that was equal to USD 600 billion (Runyan and Stehm 2020). Forest ecosystems are considered important for their NCPs though, contribution of economically relevant and quantifiable values is scarce; hence, mapping these ecosystem values are pertinent for designing appropriate conservation strategies that can appropriately include forest conservation along with sustainable use of forest produce (Strand et al. 2018). Valuation of global forest changes has been lacking despite the relevance of forest ES and NCPs (Hansen et al. 2013). There is growing relevance need to acknowledge the role of valuation of forest ecosystem good and services (Zhang and Stenger 2015). Values of nature and NCPs can never be accurately assessed hence; an inaccurate approach should be largely avoided (Costanza et al. 2017). Ambiguity due to spatial heterogeneity and data insufficiency, uncertainty for assessing ES or NCPs can also arise due various drivers influencing ES especially governance and policies. Nonmarket valuation approaches that are demand-side-based provide only gross value of forest ecosystems and not an economic value. While, many nonmarketable and nonextractive ecosystem services of forests are mostly result of opportunity costs of resources. Hence, present total forest economic value of forest ES needs to be developed from an anthropocentric instrumental valuation, differentiate gross valuation, economic valuation, and market value (Zhang and Stenger 2015). Costanza et al. (1997) estimated the value of ES for diverse biomes across the world using any one of the three approaches that included the sum of consumer and producer surplus or net rent or price time quantity. Another method is the use of forest inventories, the collection of forest data in a systematic manner following a standard protocol helps in mapping the static supply of forest services. These inventories include the services provided by the forest, services extracted from the forest, etc. (Pereira et al. 2005). Along with these traditional methods, a wide range of modeling tools have been applied to estimate the ecosystem services and their response to change in environmental and societal conditions (Crossman et al. 2013). The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model uses an ecological production function to assess ecosystem goods and services. It shows how a change in ecosystem service potential (inputs) changes the flow of services (output). InVEST so far has been used to model, sediment retention, carbon sequestration, pollination, water purification, coastal vulnerability and protection, timber production, and marine ecosystem services (Nemec and Raudsepp-Hearne 2013). Artificial Intelligence for Ecosystem Services (ARIES) is another software application that works on the principle of demand and supply and simulates a stream of ecosystem service (Villa et al. 2009). Multiscale Integrated Models of Ecosystem Services (MIMES) uses SIMILE software that quantifies the impact of changing land use patterns on ecosystem services across various spatial scales (Boumans et al. 2015). Dynamic Vegetation Models have been designed to simulate vegetation structure and functions (Kumar et al. 2018, 2020a) in association with atmospheric processes and help in quantifying the ES such as nutrient flow, carbon flux, runoff generated, and also enumerate the proxies of ecosystem health such as primary productivity (Brown et al. 2014). Universal Soil Loss Equation (USLE) is widely used to estimate the soil loss due to runoff and establish ecosystem services value (Brown et al. 2014). Future forestry research requires focus on the high values but neglected ecosystem services like mountains, grasslands, and coastal areas, “disservices”, assessing the impact of dynamic factors and disaster risks on the provision of ES, to evaluate the advantages of keeping natural forests undisturbed versus changing them to alternate uses (Ninan and Inoue 2013).

1.4 Technological Advancements in Forest Inventory and Monitoring

There is mounting call for records on area under forests, growing tree stocks, sustainability concerns, biodiversity, and climate change. Forest resources methodologies are evolving with time as per need. Conventionally, the field plot-based system was typically used for assessing of characteristics viz., tree species, tree height, canopy cover, diameter at breast height, etc. (Mackey et al. 2021). The data from forest inventory can be grounded on two comprehensive methods viz.,

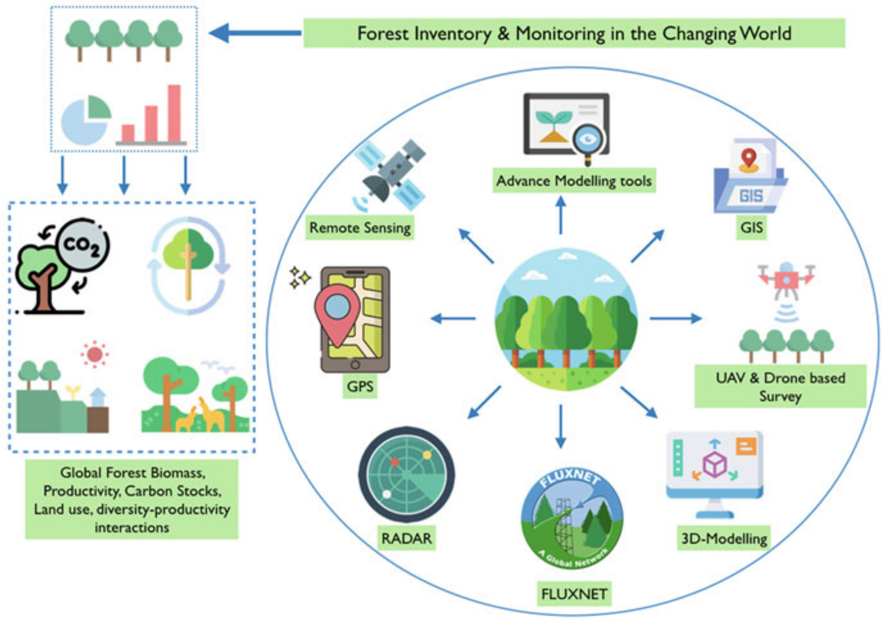

Fig. 1.2 Technological advancements in monitoring and inventorying forests in the changing world

statistical samples and stand-level data gathering where, sample-based forest inventory is broadly recognized (McRoberts et al. 2010). Though, ground survey-based, inventories in forests are detailed and precise processes of quantification till date, are strenuous, time-taking, costly, and almost impractical for a large forest area (Hussin and Bijker 2000). Remote sensing application has appeared as an important area in forestry research (Corbane et al. 2015). With the beginning of remote sensing backed forest monitoring followed by in-situ observation through flux towers, programmed sensors, and weather stations generates large amount of data that can deliver significant data linked to a landscapes. Forest informatics is close to geomatics for unfolding the spatio-temporal characteristics of forests that includes demonstration of physiological procedures and interfaces from micro to macro levels making it wider than the geomatics. Forest informatics largely covers assessing, monitoring, mapping, and modeling of forests from individual to population level by influencing the procedure of value-added computational proficiencies and informatics. Geographical Information System (GIS), Remote Sensing (RS), and Global Positioning System (GPS) provide remarkable methods to map, monitor, survey, classify, characterize, and understand changes as a fundamental part of forest informatics. Various stages of data processing and information flow depicting a typical framework of forest informatics are shown in Fig. 1.2.

RS has become a significant database because of different multispectral and artificial aperture radar sensors and platforms that include unmanned aerial vehicles or drones and satellites to map the diversity of forest variables (Lechner et al. 2020). In the previous few decades, active and passive RS approaches are used to obtain spatially precise 3D point clouds to characterize the outline of the surveyed items this has revolutionized research in the forestry sector (Díaz-Varela and González-Ferreiro 2021). 3D point clouds are increasingly being used to define forests for their measurement accurateness (Hillman et al. 2019). Various applications of RS and GIS in forestry are based on optical remotely detected information, airborne and terrestrial LiDAR, Radar, and Unmanned Aerial Vehicles (UAVs or drones) subject to the scale of mapping and size of the study area. Modeling forest ecosystems and their attributes by the combination of satellite data with machine learning algorithms (MLAs) has been advancement in remote-sensing-based forest resource assessment (Singh et al. 2021). In a recent study, forest biomass was simulated using SAR data from Sentinel-1 and optical data from Sentinel-2 using MLAs (Malhi et al. 2021). Studies are also carried out for forest assessment by using MLA, e.g., Random Forest and Support Vector Machine to project the fire proneness of forests (Gigović et al. 2019). Traditional RS tools including satellite and manned aircraft platforms are also refined in terms of their spatio-temporal and spectral resolutions. The high spatio-temporal resolutions, flexibility, and lower operational costs make UAVs a good alternative to conventional RS approaches (Guimarães et al. 2020). The rapid advancement in remote-sensing technology will result in superior democratization of RS data to support sustainable forest management and conservation in priority areas. A broad variety of RS data and products are available (Table 1.2) that can be used to monitor changing states of forest structure and function and have successfully been tested and applied extensively.

Although, modern ecology is empowered by diverse vegetation indices from operative space-based imageries still current competencies significantly magnify scientific potentials. New observations from space-based imageries allow the estimation and an idea of rough photosynthesis, carbon fluxes, forest fires, evapotranspiration to generate simulated eddy- covariance. These observations are expected to improve our knowledge of the global forest biomass, productivity and carbon stocks, land use, carbon cycle-climate reactions, diversity–productivity interactions to empower upgraded climate predictions. Developments in RS challenge ecologists to communicate data systematized by biome and species to novel data arranged by pixels for developing a theory to report formerly ignored scales (Schimel et al. 2019).

Large datasets of GHGs and energy surface-atmosphere fluxes assessed with the eddy-covariance method (e.g., FLUXNET 2015, AmeriFlux BASE) are extensively employed to standardize models and RS goods (Chu et al. 2021). The global setup of eddy-covariance (EC) flux towers has enhanced our knowledge of the global carbon (C) cycle; however, the setup has a comparatively inadequate spatial range than forest inventory database (Ferster et al. 2015). Fluxnet is a global network of scientists and researchers to share and organize flux data from "micrometeorological tower sites" at several scales (https://fluxnet.org/). Fluxnet is supported by major regional networks existing across the world. The integration of historical databases

Table 1.2 Remote sensing sensors that may be employed in monitoring forest structure and its functioning

Multispectral images (Freely available)					
Sensor	Swath width	Spatial resolution1	Period of availability	Temporal resolution	Data sources
ASTER	60 km	15/30/90 m	2000-now	1 day	https://lpdaac.usgs.gov/
MODIS	2330 km	250/500/1000 m	2000-now	Daily/weekly/16 days/monthly composite	https://earthexplorer.usgs.gov/
Landsat TM, ETM	185 km	30 m	1982–2011	16 days	https://earthexplorer.usgs.gov/
Landsat 8 OLI/TIRS	185 km	30 m	2013-now	16 days	https://earthexplorer.usgs.gov/
SPOT	60/117 km	10/20 m	1986-now	26 days	https://earthexplorer.usgs.gov/
Sentinel 3	1270 km	10 m	2016-now	<3 days	https://scihub.copernicus.eu/
LISS III	141 km	23.5 m	2006-now	24	http://bhuvan-noeda.nrsc.gov.in/data/download/
LISS IV	70 km	5.8 m	2006-now	5	
AWiFS	740 km	56 m	2006-now	5	
Commercial satellites (Available through vendors on payment basis)					
Ikonos	11/14 km	1/4 m	2000-now	3 days	https://www.digitalglobe.com
Quickbird	17 km	2.5 m	2001-now	Tasked	https://www.digitalglobe.com
Worldview 3	13 km	0.60–1.00 m	2014-now	<1 day	https://www.digitalglobe.com
Worlview 4	13 km	0.30 m	2016-now	<1 day	https://www.digitalglobe.com
GeoEye	15 km	0.4–1.0 m	2008-now	2.6 days	https://www.digitalglobe.com
Hyperspectral images (Freely available)					
Hyperion	7.7 km	30 m	2000-now	16 days	https://earthexplorer.usgs.gov/
AVIRIS	11 km	4–20 m	1992-now	16 days	https://aviris.jpl.nasa.gov/
HysIS[a]	30 km	30 m	Nov 2018	–	https://www.nrsc.gov.in/
PRISMA	30 km	30 m	March 2019-now	15 days	http://prisma-i.it/index.php/en/

[a]Data yet not available in public domain

Table 1.3 Global databases available on FluxNet

Current databases	Historical databases
• AmeriFlux • AsiaFlux • ChinaFlux • European Fluxes Database • ICOS (Integrated Carbon Observation System) • JapanFlux • KoFlux • OzFlux • RusFluxNet • Swiss Fluxnet • Urban Fluxnet • USCCC (US-China Carbon Consortium)	• BERMS (Boreal Ecosystem Research and Monitoring Sites) • Canadian Carbon Program • CarboEurope • CarboItaly • EuroFlux • IMECC (Infrastructure for Measurements of the European Carbon Cycle) • NECC (Nordic Centre for Studies of Ecosystem Carbon Exchange)

as well as presently active databases is incorporated in database viz., the European Fluxes Database. A few of the regional networks are listed in Table 1.3.

1.5 Changing Forest Structure and Functions

In the last more than 8000 years, collective loss of forests has amounted to almost 2.2 billion hectares, decreasing forest cover from 47% to 30% of the planet's surface by 2015 (Runyan and Stehm 2020). Severe human-induced pressures coupled with global climate change have resulted in extraordinary and unforeseen impacts on natural forest ecosystems, demanding innovative ecological engineering approaches, genetic conservation of trees followed by landscape methods that focus on constructing functional landscapes and ecosystems in an economical way (Löf et al. 2019). Despite the immense value of forests, they are undergoing unprecedented rates of deforestation with that is equivalent to an annual loss of 2101 km^2/year (Caron et al. 2021). Forests provide a diverse range of ecosystem services at local, regional, and global scales, including hydrological, climatic, biogeochemical, biodiversity, and ecosystem stability and resilience. The long-term damage to natural forests is negatively affecting communities and countries (Runyan and Stehm 2020). Human land use has fragmented the forests across the world, enhancing the edge density and augmenting the presence of edges in natural forest ecosystems. Permanent as well as transient edges in forests have a substantial impact on forest ecosystems that needs to be deliberated explicitly in the analysis and management of these forests (Pöpperl and Seidl 2021). Forest structural changes affect the growth and carbon stock of natural forests (Cheng et al. 2013). Present approximations of CO_2 emissions from deforestation and forest degradation are commonly grounded on inadequate evidence and are described by extraordinary ambiguity (Duarte et al. 2020). The spatial disparity in forest structure yields small-scale ecological heterogeneity, which distresses the survival of plants and their propagative routine

(Rodrigues et al. 2014). Jointly, these developments in forest cover and forms are of foremost worry, because of the repercussions for biodiversity conservation, but also a wide variety of critically essential ecosystem services (Brockerhoff et al. 2017). Human-induced pressure has affected the tropical forest ecosystem in terms of degradation, deforestation, and fragmentation (Eguiguren et al. 2019). The concept of forest degradation tends to be addressed in broad terms, as degradation is the result of a progressive decline in the structure, composition, and functions upon which the vigor and resilience of a forest is based (Vásquez-Grandón et al. 2018). Land use change is a mega driver of loss of spatial configuration and inclusive provisioning ecosystem services (Lawler et al. 2014). Loss of habitats, by alteration of tropical forests, has resulted in the biodiversity crisis we are observing today (Estavillo and Pardini 2013). Human-induced interferences have previously triggered ample loss of biodiversity and homogenization (Brockerhoff et al. 2017). Globally, marginalized communities are feeling a deficit of critical ecosystem services especially reduced water provisioning, affecting human well-being because of the loss of natural forests to commercial plantations (Alfonso et al. 2017). Forest ecosystems across Asia are susceptible due to diverse drivers of loss, which enhances the possibility of the elimination of species (Hughes 2017). Deforestation is influenced by several multifaceted direct and indirect causes. Expansion of agriculture (both commercial as well as subsistence) is considered key driver, followed by quarrying, infrastructure buildup, and urban sprawling. In turn, people and financial development initiate the call for agriculture, quarrying, and timber, and supporting infrastructure. Exponential population growth and shifting consumer interests enhance global nutrition demand necessitating a net intensification of arable land under agriculture. Deforestation is exaggerated by other dynamics such as land lease uncertainties, inappropriate governance, low capability of civic forestry interventions, and insufficient arrangement and monitoring (Runyan and Stehm 2020). The deterioration in old-growth forest areas, and the intensification of managed new forest missing natural postdisturbance structure, characterizes foremost alteration in the biological environments of the forest outside their chronological boundaries of changeability. This may bring risk to ecosystem resilience and biodiversity along with the longstanding adaptive ability of these forests (Kuuluvainen and Gauthier 2018). The annual frequency of clear loss of forests has reduced from 7.3 M ha year^{-1} in the 1990s to 3.3 M ha year^{-1} from 2010 to 2015. Natural forest areas have dropped from 3961 M ha to 3721 M ha from 1990 to 2015. While planted forest areas have augmented from 168 M ha to 278 M ha. From 2010 to 2015, tropical forest areas have dropped at a frequency of 5.5 M ha year^{-1}, that is 58% of the frequency from 1990s whereas, temperate forest areas have stretched at a proportion of 2.2 M ha year^{-1} (Keenan et al. 2015). It is significant to note that though global magnitudes of tropical deforestation remain distressing and astonishing, they have reduced from 2000 to 2010, and not many tropical emerging economies have lately been through a forest shift from clear deforestation to clear reforestation (Meyfroidt and Lambin 2011). Various case studies have revealed that ecosystem degradation has reduced its capacity to act as a buffer

Table 1.4 Assessment of benefits and overall trend of various ecosystem services

Ecosystem services	Benefit	Overall trend
Food	Positive trend	Ambiguous
Freshwater	Negative trend	Negative
Moderation of extreme events	Ambiguous trend	Ambiguous
Soil fertility	Negative trend	Negative
Wastewater treatment	Neutral	Negative
Biological control	Positive trend	Positive
Pollination	Positive trend	Ambiguous
Recreational and physical health	Positive trend	Positive

Adopted from Shepherd et al. (2016)

against extremes climatic events (MEA 2005). Few prominent services and their global trend are presented in Table 1.4.

An emerging trend of exploitation of ecosystem services and the simultaneous decline in the potential of the ecosystem to maintain their sturdy flow led to irreversible changes (Pereira et al. 2005). Condition overlying-narrow focus on few services led to the loss of other services which sometimes result in the sudden collapse of the system and regime shift (Gordon et al. 2010). Many forest ecosystems are at risk of ecological collapse, which can be defined as a sudden, long-term, and broader change in ecosystem structure and processes that can negatively affect biodiversity and critical ecosystem services (Lindenmayer et al. 2016). Collapse can be reflected in the obvious changes in ecosystem situation, predominantly the speedy degeneration of species populations that are keystone and support ecosystem structure and functions. There also has been a substantial deterioration of biodiversity that has been intensely related to these arrangements and interferences of key ecosystem functions (Lindenmayer and Sato 2018).

1.5.1 Deforestation and Forest Degradation

Deforestation and forest degradation are issues of global concern and key indicators and facilitators of loss of natural forest ecosystems (Mitchell et al. 2017). Deforestation leads to replacement of forest land use whereas forest degradation results in reduction of forest canopy cover as well as loss of forest carbon stocks (Shimabukuro et al. 2019). Forest degradation in developing economies, especially the ones in tropical and subtropical zones, is fundamental contributor to global GHG emissions (Pearson et al. 2017). Forest ecosystems can be degraded because of several drivers of loss; these can be direct as well as indirect drivers (Kumar et al. 2021b). Drivers of deforestation are quite similar across African and Asian countries, while drivers of forest degradation were found comparatively of similar nature in Latin American as well as Asian countries. Commercial agriculture has emerged as the mega driver of deforestation that is followed by subsistence agriculture practiced by local communities. Extraction of wood for timber by logging drives forest

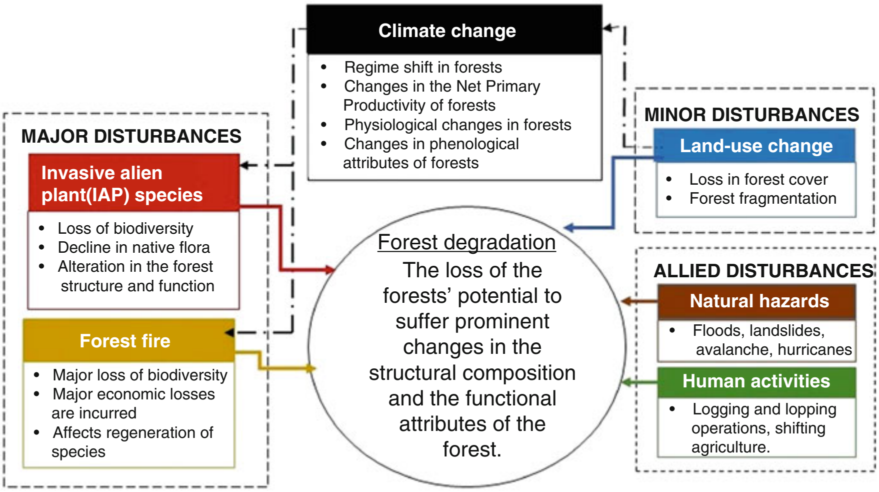

Fig. 1.3 Deforestation and forest degradation as influenced by multiple drivers of loss of biodiversity and ecosystem services

degradation, followed by collection of fuelwood and for production of charcoal, man-made forest fires, and grazing by cattle (Hosonuma et al. 2012). Deforestation and degradation have significantly reduced the tree carbon stocks; however, tree growth, restoration, and expansion of forests can counterbalance these massive losses (McNicol et al. 2018). The assessment of degradation of forests, its dynamics, and proximate causes can support rapid and early efforts to mitigate GHG emissions to assist formulation of appropriate land use policies (Shapiro et al. 2021). Countries across the world are encouraged to identify potential drivers of deforestation and forest degradation for developing national strategies as well as action plans for REDD+ (Hosonuma et al. 2012). A different disturbance that may lead to degradation of forests is depicted in Fig. 1.3.

Enhanced human-induced interferences in the forested landscapes have blurred the boundary between anthropogenic and natural impacts of forest disturbance and presently both of them exist and impact the ecosystem in a synergistic manner. Understanding of scientists and foresters about forest disturbance dynamics in response to climate change is insufficient, especially about its large-scale interactions and impacts (Seidl et al. 2017). Ecological memory has been considered relevant for ecosystems the way they respond to disturbances that is governed by important legacies that include information as well as material. Disturbance factors that help to preserve these legacies have the capability to enhance ecological resilience for ecosystem recovery. However, these legacies can get lost with the change in disturbance regimes leading to a condition of "resilience debt" that emerges only after the ecosystem gets disturbed (Johnstone et al. 2016). Forest disturbances require specific attention because of their structural complexity to other terrestrial ecosystems viz., agriculture or grasslands (Frolking et al. 2009).

Some of the relevant disturbances that are capable to modify forest structure and functioning are briefly discussed in forthcoming sections.

1.5.1.1 Forest Fire

Massive and widespread fires are result of warm and dry conditions that will be further amplified by increasing frequency and intensity of climate change (Halofsky et al. 2020). In the last few decades, this natural forest fire phenomenon has attracted global attention because of its increasing size, intensity, and frequency (North et al. 2015). As climate change results in enhanced warming disturbance because of forest fire increases too leading to disturbed C dynamics in fire-prone areas. Forest fires will likely affect and bring significant implications for the global carbon budgets and cycles contributing to climate change and enhancing vulnerability (Walker et al. 2020). Forest fires are mostly restricted to the ground and the understory, wherein the canopy does not get affected (Frolking et al. 2009). On the contrary, crown fires ascend to the forest canopy and severely affect the canopy cover in the process (Frolking et al. 2009). Forest fire is capable to affect ecosystem structure, diversity, composition, processes, and functions by identifying fire-adapted plants and replacing susceptible plant species, releasing nutrients and improving biogeochemical cycles, affecting soil properties by changing soil microbial flora, its structure and functions, water associations, and developing diverse heterogeneous mosaics, that can further influence forest fire behavior and ecological processes. Fire can result in loss of massive biomass and many negative consequences viz., postfire soil erosion as well as water runoff, followed by emissions that pollute air environment. However, as a constructive impact forest fire can help to maintain the ecosystem health of fire-dependent ecosystems (Chen 2006). With increasing frequency of forest fires across the world, fire is likely expected to negatively affect diversity of trees in existing forests that are selectively logged. This can affect regional carbon budgets and cycle that will largely affect the global forest carbon sink (dos Santos Prestes et al. 2020). The spatio-temporal understanding of forest fires needs more research to develop strategies for better agriculture yields and to understand postfire successional patterns (Juárez-Orozco et al. 2017). The spatial heterogeneity of fore fire is because of the intensity of the forest fire, rate of spread, and its susceptibility to forest trees (Oliver and Larson 1996). Forest biomass was reported to be reduced by 46% by forest fire and by 80% on reoccurrence of forest fires. Forest regeneration was observed to have lasted for more than 100 years to get restored to prefire state. Productivity of tree biomass and respiration rates were reported to have increased by four times postfire than before because of the presence of pioneer species. It was observed to take more than 150 years for compensating the GHG emissions due to forest fires. Functional diversity was reported to enhance after forest fire; mostly fire-tolerant pioneer species dominate fire-affected area changes the course of forest succession (Fischer 2021). Socio-economic drivers, deforestation, followed by global climate change should be integrated in forest fire research to develop a comprehensive understanding on forest fires (Juárez-Orozco et al. 2017). There are many gaps in our understanding about forest fires and their impact on forest understory, its interaction with fire, and long-term impacts of forest fires. It is critical and relevant to evaluate and develop understanding of present and future response of forest fires on structure and functioning of natural forest ecosystems (dos Santos Prestes et al. 2020).

1.5.1.2 Invasive Alien Species

Globalization followed by rapid upsurge in international transportation and trade has enormously enhanced in invasion risks (Shackleton et al. 2014). Invasive alien species (IAS) are important global and local driver of biodiversity loss (Langmaier and Lapin 2020). Forest fragmentation results in invasion of exotic plants by enhancing their seed dispersal and availability of resources besides the boundaries. These effects differ for different forest age classes and are subjective trait differences of native and nonnative plant species (Dillon et al. 2018). Invasive species are able to affect local biodiversity on multiple scales and diverse ways (Kumar et al. 2019c). In natural forest ecosystems, risks due to IAS comprise of hybridization, disease transmission, and competition among species (Langmaier and Lapin 2020). Ecosystem processes are disrupted from IAS due to decline in native floral richness, and modification of community structure (Hejda et al. 2009). On a larger spatial scale, IAS are inclined to homogenize the region by adversely affective natural course of regeneration, by directly regulating the growth or secondarily by enhancing regeneration struggle (Dyderski and Jagodziński 2020). The complicated interactions within an ecosystem suggest that disturbance at one place by IAS leads to cascading consequences that negatively effect the flow of critical ecosystem services (Charles and Dukes 2008). Human impact on the IAS establishment is prominent and many planted forests are managed by them. Planted and managed pine plantations are less vulnerable to IAS as closely examined, controlled, and managed by humans. Hence, it is claimed that early warning systems for IAS can be included in these managed planted forests (Martínez-Jauregui et al. 2018).

1.5.1.3 Land Use Land Cover Change

Land use and land cover changes (LULCC) moderate and regulate ecosystem services and associated landscape processes (Zhao et al. 2020). LULCC reveals and shapes comprehensive interaction between commercial growth and conservation of biodiversity. By second half of the twentieth century, search of commercial expansion leads to transformation of ~24% of the earth's surface into agriculture and damage to ~35% of coastal mangroves and ~20% of vulnerable coral reefs. During the same time, worldwide GDP augmented sixfold (with a normal 3.9% annual development rate), yet the worldwide "aggregate capital stock" fallen as the economic growth from the reduction of natural capital was frequently consumed than being capitalized in alternate investments (Tesfaw et al. 2018). It is progressively recognized that LULCC is a crucial topic that immediately needs consideration in global climate change (Hu et al. 2019). The LULCC for a region is consequence of its natural and socio-economic characteristics and their spatio-temporal processing (Tewabe and Fentahun 2020). The human-induced interferences on biosphere have tremendously augmented in the last 300 years at an astounding frequency. Histrionic and exponential population growth has come at the price of natural forests and grassland ecosystems. During the previous 300 years, approximations for the global reduction in forested area range from 8 to 13 million km^2, that corresponds to 15–25% of the actual extent of 1700 (Goldewijk and Ramankutty 2010). Though alteration of land by people for subsistence livings and other necessities has been there for the last thousands of years; the magnitude, intensity, and frequency of LULCC were far less than in the present. These changes are mega drivers of exceptional alterations in ecosystem structures and processes at local, regional, and global level (Hassan et al. 2016). Frolking et al. (2009) classified land conversion of forests into two categories, permanent as well as temporary. Permanent land conversion referred to the forest land altered to nonforest use permanently, such as oil palm plantations, mining, industrialization, etc. (Fitzherbert et al. 2008). Temporary land transformation was by conversion of forest land for a few years. Human-induced forest disturbance, permanent forest land use transformation are global concerns, but short-term forest conversion is mostly limited to tropical as well as subtropical regions of the world (Lanly 1985). Anthropogenic LULCC distresses global climate as well as terrestrial carbon cycle (Quesada et al. 2018). Progressively, forests are part of international climate change agenda as LULCC leads to loss of forests as well as terrestrial carbon (Syampungani et al. 2014). Accepting the extent, course and means of LULCC are required for recognizing the reasons of alteration and planning efficient strategies and schemes to reduce, halt, and reverse land degradation to achieve land degradation neutrality and by forest landscape restoration (Mekonnen et al. 2018; Betru et al. 2019). Reducing emissions from deforestation and forest degradation (REDD+) plus preservation of forest carbon stocks, sustainable administration of forest ecosystems by enhancing forest carbon stocks in developing countries necessitates evidence on LULCCs and carbon emission drifts from historical to the present and into the forthcoming years (Capitani et al. 2019). Sustainable land management policies for future should consist of learning on the importance of the natural forest ecosystems, participatory efforts in sustainable consumption of forest ecosystem services by introducing alternate sources of sustainable livelihood opportunities from natural forests (Masayi et al. 2021).

1.5.1.4 Climate Change

The prime force which functions to shape the biomes of the world is climate (Hansen et al. 2001). Changing temperature and rainfall patterns followed by aggregate concentrations of atmospheric CO_2 will drive significant alterations in natural forests (Kirilenko and Sedjo 2007). There is growing international focus on forests in all the high-level multilateral pledges for nature and from a climate standpoint, this attention on forests is extremely significant. Because of their importance as both carbon source as well as sink, they are ever more in the glare of publicity and have a crucial role to play in the global climate change strategy (Seddon et al. 2019). Climate change has pressed additional stress on the previously lost natural forest ecosystems. However, it is typically unidentified how climate change will distress the spatial distribution of natural forests in the forthcoming years (John et al. 2020). Professionals have ranked the paramount and most probable climate change effects on the forest production that includes: forest health risks enforced by pests and pathogens, dangerous rainfall events, alterations in the forest structure and composition, IAS, and fluctuations in forest productions (Soucy et al. 2021). Significant ecosystem services from natural forests are expected to affect due to climate change, possibly because of the influence of surges in atmospheric CO_2 on plant physiology (Yu et al. 2021). Climate change is anticipated to considerably modify tree spatial distribution in coming decades (Dhyani et al. 2018, 2020b; Baumbach et al. 2019). Secondary forests experiencing successional alterations are going to be the main factors in the present global carbon cycle. However, functions of these forests in the forests in warmer situations with greater atmospheric CO_2 concentrations are unidentified (Mohan et al. 2012). Climate plays a crucial role functionally in diverse plant processes like phenology (Mohanta et al. 2020; Kumar et al. 2019d, 2021c), net primary productivity, etc. (Kumar et al. 2018). Kumar et al. (2018) described that 80% of the forests in the Indian Western Himalayan region are vulnerable to climate variability, and not even half of them have ample resilience to climate change. Many biogeographical models validate shift of potential forest vegetation to arctic region due to climate change. The equilibrium as well as some other dynamic vegetation models predict this vegetation shift to a fresh accessible zones with promising climate situations will ultimately effect forest growth and replacement of approximately 50% of prevailing vegetation in the north. Growing atmospheric CO_2 concentrations, apart from altering the temperature and rainfall patterns, might also upsurge production by "carbon fertilization effect" (Kirilenko and Sedjo 2007). Due to climate change, the occurrence and strength of climate extreme events have also augmented (Stocker 2014). Influencing an ecological outlook of climate extremes is complex due to varied nature of impacts, which vary from in significant distresses to ostentatious disturbances that are able to alter the structure and function of natural ecosystem (Folke et al. 2004). Such major modifications had been observed in the forests of United States of America, where due to an upsurge in the frequency of tropical cyclones, an ecological regime shifted leading to conversion of coastal mangroves to mudflats (Osland et al. 2020). A major limitation to study climate-forest interfaces is the insufficiency of data (Kumar et al. 2018). The limitation merits establishment of inventories, while the difficulties in the understanding of climate change call engagement of modern and advanced scientific tools and technologies.

1.6 Structure of the Book

This book volume has 22 chapters on diverse topics related to forest dynamics and conservation and is divided into four sections. The book volume includes a detailed introductory chapter providing background on forest dynamics and conservation science, and innovations for reducing deforestation and forest degradation by Kumar et al. (this chapter). This chapter covers insights on global deforestation and forest degradation issues followed by technological advancements in monitoring and inventorying forest resources. The chapter also deliberates on the ongoing developments on the core themes of diverse forest dynamics and conservation issues. Part I of the book highlights "drivers of deforestation and forest loss" for understanding forest degradation and its drivers that are essential to ensure responsive, effective, and efficient forest activity concerning a more amiable diverseness and climate outcomes presented under seven important chapters (Chaps. 1–7). Samuel (Chap. 2) in the opening chapter of the section presents an overview of different definitions, indicators, assessment methods, and drivers of forest degradation that addresses the need for an apt and clear understanding of this pertinent topic in the warming world. Huettmann and Young (Chap. 3) bring focus to old-growth forest wilderness areas that are on a rapid global decline. He provides insights into science-based sustainable forest management (SFM) that is practiced worldwide through ground truth examples of how the practice is not sustainable on finite landmass. Chatterjee et al. (Chap. 4) provide an overview of synergistic impacts of pollutants, climate change, and decimation of forests and its after-effects, i.e., forest dieback, invasion by invasive species including pests and pathogens, and low regeneration of forest trees through a case study of Gangetic plains of India that is a global ammonia (NH_3) hotspot. The chapter by Prieto and Florin (Chap. 5) addresses the growing issue of wildfires and designing a sustainable future by solutions based on forest-society relationships. The chapter addresses these issues by searching for proposals which are based on forest-society relationships, by a novel compilation of the extension and temporal dynamics of forest fires and their major types in the context of main weather, biogeochemical, and plan communities' aspects in a representative case study, and the international scope and decadal evolution of surface affected by forest fires in both absolute terms and in proportion to the total forest surface, followed by understanding the integrated implications of social and economic factors and forest policies. Chapter 6 by Kalpana Giri questions the gender agenda of Nepal's Community Forestry that is at risk due to commercial transitions? The chapter examines the reasons behind such framing and identifies its implications to gender agenda in Community Forestry. The author also suggests revitalizing the gender agenda by accounting for the economic costs of forest management and positioning women and marginalized groups in new economic roles. Chapter 7 by Dhyani et al. addresses an important issue of forest soil microbial diversity or gene pool as the association of the genes facilitates and may also alter important processes such as energy flow, biogeochemical cycles, and signaling secondary metabolites. Authors highlight different components of the forest ecosystem, their interplay, and their impact on soil structure and function, thus affecting different ecosystem productivity. Part II of the book under the title "Forest and Sustainability Concerns" is comprised of five chapters (Chaps. 8–12). The opening chapter in the section by Calixto and Hahn (Chap. 8) presents an overview and perspectives on plant-herbivore interactions in a forest ecosystem to sustain losses. The chapter highlights the plant-herbivorous insect interactions, with a background of how studies focusing on the ecology and evolution of interactions are important to understand the processes that drive species diversity. Authors also discuss the coevolutionary process between plants and insects by describing how plant-herbivorous insect coevolution can promote species diversity and shape ecosystems, and the potential mechanisms by which plants and herbivores might influence the ecosystem structure and biodiversity, which can act as a proxy for conservation measures. Chapter 9 by Sapkota et al. unpacks the social dimension of forestry and its implications to forestry management and discusses multiple roles of community forestry in different contexts, through case studies completed in Cambodia, Myanmar, Nepal, and Vietnam in tackling climate impacts and COVID-19 restrictions. Murthy et al. (Chap. 10) bring in the important dimension of biodiversity and biomass carbon dynamics by presenting insights from long-term monitoring in Western Ghats, India. Authors insist creation of policy, decision, and networking windows to allow the use of information from permanent plots for effective and efficient management of forest ecosystems and making them resilient to systemic and chronic shocks both climate and nonclimate. Chapter 11 by B. Dhanya presents a case study of urban protected forests by projecting the ramifications of urban growth on social-ecological interactions around periurban protected areas (PAs). The authors discuss the implications of urbanization for biodiversity conservation and ecosystem-dependent livelihoods in periurban spaces and suggest ways to integrate protected forests in the urban fabric. Kumar et al. (Chap. 12) are on mapping the extent of invasive species even from pristine settings of Eastern Himalayas, India. Results presented in the chapter demonstrate the suitability of Red-Edge Band of Worldview-2 images to discriminate invasive species in mixed vegetation that can assist in the management of infestation in the high-altitude region. Part III of the volume is dedicated to “Insights to Innovations” to study forest ecosystems and also reduce deforestation and forest degradation. The section covers seven important chapters (Chaps. 13–19) and the opening chapter of this section is by Shukla et al. (Chap. 13). Chapter brings attention to the Groundwater-Dependent Ecosystems (GDE), needs to study them, their classification, identification methods, along with the global advances in GDE’s mapping and groundwater allocation trends highlighting the need for GDE assessment in water-dependent agrarian economies across the world facing water stress due to burgeoning population and subsequent rise in human water demand. Khaiter and Erechtchoikova in Chap. 14 of this section carefully consider the synergistic perspective of advanced scientific methods and tools in sustainable forest management. Framework accommodates various contributing concepts, such as sustainable development, forest ecological-economic-social systems, forest ecosystem services and benefits, forest informatics, precision forestry, adaptive forest management, and data science followed by a nine-step roadmap for practical implementation of the framework. Tyagi et al. in Chap. 15 cover a coherent view and application of dynamic vegetation models for the climate change impact assessment specially to understand widespread implications for the structure and function of vegetation all over the world. Chapter 16 by Harun et al. reflects on Peatland ecosystems through a case study from Indonesia and highlights the role of agroforestry approaches for peatland landscapes restoration. The chapter discusses the performance of six tree-based agroforestry types practiced in the peatland landscape of Central Kalimantan, such as jelutong tree-based agroforestry, agro-silvopastoral, agro-silvo-fishery, and apiculture system of tree-based agroforestry types in Central Kalimantan. Kala and

Mukhopadhyay in Chap. 17 present SmarteR approach for the mapping of invasive plant species and provide an overview on diverse modeling techniques along with model evaluation using R language and platform. Chapter 18 by Singh et al. highlights the challenge of mapping and identifying different tree species based on their canopy characteristics with the high spatial resolution data and presents the artificial intelligence-based semantic segmentation deep learning method to map and identify trees. The chapter also deliberates on the potential of artificial intelligence-based semantic segmentation deep learning method to be utilized for studies of paramount importance like the census of trees. The concluding chapter of this section is by Reddy et al. (Chap. 19) that discusses the application of biophysical, soil, and vegetation indices to better understand forest dynamics and develop strategies for forest conservation. The chapter discusses how remote sensing spectrum imaging techniques can be used to analyze a variety of biophysical and vegetation indices to plan and monitor various forest management operations. Last Part IV of the book volume includes the chapters with a focus on "Advanced institutional provisions and governance framework" for forest dynamics and conservation. Part IV includes three relevant chapters (Chaps. 20–22). Chapter 20 by Adhikari and Baral is a case study from Nepal on World Bank's Forest Carbon Partnership Facility on its Emission Reductions Program (ER-Program). The chapter discusses the mega drivers of forest loss and highlights the potential of ER-Program to address the drivers of emissions-causing deforestation and forest degradation and enhance forest carbon stock, ultimately paving the way for results-based payments for future emissions reductions for Nepal. Scandizzo and Abbasov in Chap. 21 of this section bring insight into the Public Interests and Private Incentives in Designing an Ecological Payment System. The chapter assesses the main opportunities for a Payment of Ecosystem Services (PES) in selected areas of Azerbaijan and investigates its impact, development, and potential through an implementation approach. The last chapter of this section (Chap. 22) by Isa et al. covers the importance of the awareness and Conservation Program at Ecotourism Sites through a case study example from Langkawi Island, Malaysia. The chapter stresses the need for more planned awareness and conservation programs to enable tourists and ecotourism operators to appreciate and have a better understanding of taking care of the environment at ecotourism sites. We are sure this makes a great read for finding diverse concepts and innovations related to forest dynamics, conservation science, innovations, and policies for reducing deforestation and forest degradation all compiled in a single volume.

Through this book volume, editors, as well as authors, expect a satisfactory response and if also possible feedback from readers belonging to diverse backgrounds and fields for encouraging productive critiques, that facilitates intuitive and foresighted professional discussions for forest dynamics, conservation science, innovations, and policies for reducing deforestation and forest degradation by identification of new research issues to fill the existing gaps.

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Part I

Drivers of Deforestation and Forest Loss

2 Understanding the Drivers of Forest Degradation

Oluwayemisi Samuel Olokeogun

Abstract

Forests provide critical support for human survival as well as habitat for flora and fauna. However, due to ever-increasing anthropogenic pressure, these are under stress and face a variety of threats. They may not be able to support essential ecosystem services in the absence of an adequate conservation plan, necessitating immediate attention. Forest degradation is accelerated by the extraction of fodder, fuel, non-wood forest products, insect/pest attack, forest fire and climate change. The magnitude of these degradation pressures and drivers varies globally, as do their consequences. This provides an opportunity to better understand forest degradation and its drivers, allowing for better management planning and achievement of a specific goal. Understanding of forest degradation and its drivers is essential for the development of guidelines that ensures responsive, effective and efficient forest activity in relation to a more amiable condition and to support climate change mitigations. There are many different perceptions and interpretations on forest degradation emanating from various research fields, which reveal the need for an apt and clear understanding of this field. Forest degradation in the form of disturbance sometimes has different meaning in different context. This chapter discusses various definitions, indicators, assessment methods and drivers of forest degradation in order to facilitate a better understanding of goal-specific actions for forest management.

Keywords

Deforestation · Landscape · Forest policies · Climate change · Forest management

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2.1 Defining Forest Degradation

There is no universally accepted definition of forest degradation (Acharya et al. 2011; Duguma et al. 2019), making it difficult to define levels of forest degradation. Defining forest degradation is a challenge since it comprises of multiple intricate processes which are difficult in terms of detection and measurement. The humongous nature of the term implies that a singular definition may not necessarily hold true in various contexts. The complex nature of forest degradation has led to the emergence of multiple definitions of the same (ITTO 2002; IPCC 2003; Putz and Redford 2010; FAO 2011; Thompson et al. 2013; Khuc et al. 2018). Hosonuma et al. (2012) defined forest degradation as carbon loss and canopy trimming in the remaining forests of a damaged forest with the intention of re-growing it.

Khuc et al. (2018) outlined it as a drop in the production capacity of a forest expressed by numerous measures as well as change in forest vegetation types, reduction of carbon stock and forest quality. Forest degradation was also defined as a distinct, omnipresent and increasing pattern of anthropological disturbance of forest scenery (Matricardi et al. 2020). Parrotta et al. (2012) explained it as the reduction in forest capacity in providing vital ecosystem services caused by either anthropogenic or natural disturbances. Matricardi et al. (2020) expressed it as a momentous form of landscape and ecosystem disturbance. Brinck et al. (2017) termed it as a subordinate consequence of deforestation in fragmented forests which creates segregated forest patches and edge outcome.

Profoundly, forest degradation has been extensively acknowledged as a significant form of disturbance (Longo et al. 2016; Baccini et al. 2017; Rappaport et al. 2018; Matricardi et al. 2020). It is considered as a critical topic with regard to the examination of attempts being made to improve forest ecosystem resilience or reduce carbon emissions (Acharya et al. 2011). It has adversative, and corresponding, ecological, environmental and social implications, causing variations in the function, structure and other qualities of a forest (Acharya et al. 2011). Forest degradation is recognised based on reduction of forest capacity to provide all ecosystem services (Acharya et al. 2011), essential for environmental protection and income generation (Etongo Bau Daniel 2016). Forest degradation occurrences might possibly recur with capricious incidences at the same site and occasionally after some years, dissimilar forms might overlap spatially (Matricardi et al. 2020). Forest degradation is not binary, but rather a continuum (Bustamante et al. 2016).

Globally, about 100 million ha of forests are affected by forest degradation annually (Nabuurs et al. 2007; FAO 2006). Due to its role in global warming, forest degradation in the tropics has gained worldwide recognition (Etongo Bau Daniel 2016), by contributing about 20–25% of annual greenhouse gas emissions (Grieg-Gran 2008; Etongo Bau Daniel 2016). In most developing nations, it is considered as a leading emissions source (Karousakis 2006; Etongo Bau Daniel 2016). More than 60% of forest degradation in tropical region takes place beyond forest concession extents (Hosonuma et al. 2012; Etongo Bau Daniel 2016) and continues to be influenced by small-scale agriculture (DeFries et al. 2010; Kissinger et al. 2012).

An understanding of forest degradation drivers is vital and necessary for developing measures and policies that enable humans to amend present trends in forest operation leading to a climate and biodiversity-friendly result (Rudel et al. 2009; Kissinger et al. 2012; Kumar et al. 2019a). The types of forest degradation driver greatly influence forest carbon impacts, choice of data sources and adopted measuring and monitoring methods. When forest degradation activities are identified, easily measured indicators can be developed (Morales-Barquero et al. 2015). Importantly, the rates of forest degradation intensely increase by synergisms among simultaneous disturbance vectors (Bustamante et al. 2016).

2.2 Indicators of Forest Degradation (Key Forest Degradation Elements)

Forest degradation takes place inside forests and is distinguished by biomass loss within a complete canopy (Longo et al. 2016). Important indicators (elements) of forest degradation include, loss of canopy cover, loss of ground vegetation or understory, poor regeneration, loss of capacity to produce forest products, loss of reproductive potential and tree species, loss of potential to sequester carbon, loss of potential to conserve biodiversity, loss of potential to harvest water, loss of potential to realise recreational value, declining population of tree species, alteration of water and energy balances, increasing incidence of infectious disease, increased vulnerability to fire, the release of greenhouse gases, loss of biodiversity, declines in ecological, social and economic services and others (Nobre et al. 1991; Nepstad et al. 1999, 2001; Cochrane and Schulze 1999; Houghton et al. 2000; Tavani et al. 2009; Matricardi et al. 2010; Acharya et al. 2011; Alencar et al. 2011; Laurance et al. 2012; Nobre Carlos et al. 2016; Pfeifer et al. 2017; Castro et al. 2019; Olokeogun and Kumar 2020; Kumar et al. 2019b, 2021a).

2.3 Degradation Assessment Methods

Forest degradation is complex and challenging to measure, monitor and assess (Lambin 1999; Souza Jr et al. 2003; Panta et al. 2008; Acharya et al. 2011; Matricardi et al. 2020). The assessment methodologies for direct drivers (Table 2.1) include field survey, aerial photography, satellite image and ecosystem service valuation (Acharya et al. 2011), while indirect drivers rely more on data sources, economic and social indicators, statistical analysis and modelling (Soares-Filho et al. 2006; DeFries et al. 2010; Rademaekers et al. 2010; Kissinger et al. 2012). Accurate estimates of the influence of forest degradation on carbon stocks can be obtained by measuring individual and combined effects of diverse drivers, although it poses a great challenge and necessitates combination of different approaches (Bustamante et al. 2016; Pokhriyal et al. 2020). Evaluation of drivers is mostly centred on local or provincial case studies (Geist and Lambin 2002; Kissinger et al. 2012; Kumar et al. 2021b) or harsher evaluations on the continental

Table 2.1 Methodologies for assessing direct drivers of forest degradation (Adopted from Acharya et al. 2011)

Techniques	Merits	Demerits
Field studies	• Available of data for comparison • Better precision • Generally understood • The technology is simple • All categories of ecosystem services are captured • Suitable for local and national scales • Involves reduced labour cost • Substantial experience • Availability of research data and case study data	• It consumes time • Requires more resources • Recent data are not available • Tedious in mountainous area
Aerial photography	• Easy to understand • Easy to exhibit • Extensive experience • Low input is required	• Very costly • It takes long time • Tedious in mountain terrain • Obsolete technology • Some elements of degradation are not completely detectable
Digital image processes and GIS	• Very easy to interpret • Generally uniform • Fast developing technology • Data are provided at consistent intervals • Low forest inventory is required	• Requires high technical skills and infrastructure • Requires little control plots for ground-truthing • Provides seasonal imagery • Tedious to assess understory and non-timber forest products (NTFPs)
Ecosystem services valuation	• Wider forest ecosystem values are captured	• Requires high technical skills

and international scales (DeFries et al. 2010, Rademaekers et al. 2010; Kissinger et al. 2012) with lesser attention on the national level.

Many variables impact the approach used to monitor or evaluate forest degradation, including the amount of existing data, the kind of deterioration, the investigator's skills and the resources available (Mercedes et al. 2016). The precision of forest degradation assessment increases if methods are combined (Acharya et al. 2011). For instance, combination of both field and remotely sensed data in measuring current rates of forest degradation is able to lessen uncertainties in provincial and national estimates (Asner and Alencar 2010; Bustamante et al. 2016). Morales-Barquero et al. (2014) suggested that the best approach for measuring forest degradation is to measure against a local standard area(s) characterised by little or no degradation, with similar biophysical characteristics. According to DeFries et al. (2007), an effective monitoring system for forest degradation involves employment of multiple techniques and sometimes in combination too. These range from satellite remote sensing (SRS) to field and arithmetical models, established and built on vigorous field-based datasets (Kumar et al. 2021a).

Forest degradation monitoring systems based on remotely sensed or in-situ data or combination depend upon active definitions restricted by the responsiveness of the measurement approaches employed (Bustamante et al. 2016; Joshi et al. 2021; Singh et al. 2020a, b, c). Effective observation of forest degradation should be linked to feasible quantifiable measurement approaches (Bustamante et al. 2016). Assessment and monitoring of forest degradation in developing nations bank on remote sensing (RS) approaches mixed with up-to-date field assessments of carbon stock variations, due to lack of reliable past monitoring and land-cover data (Herold et al. 2011).

Spatial assessments of forest degradation using remotely sensed and ground data are useful in capturing the spatiotemporal relations between direct drivers, trailing their effects over a period and for supporting strategies to reduce emissions, especially at regional level. The accumulating use of SRS tools guarantees a better national level monitoring of forest degradation happenings and types, including actions that trigger them (Hansen et al. 2010; Gibbs et al. 2010; Kissinger et al. 2012). Though airborne remote-sensing and SRS skills together with field measurements may not provide the anticipated precision to evaluate and observe changes due to forest degradation, but they possess strong potential for large-scale assessment (DeFries et al. 2007; Asner and Martin 2009; Goetz et al. 2009; Saatchi et al. 2011; Baccini et al. 2012; GOFC-GOLD 2013). RS may possibly provide data at consistent intervals, allowing countries to recurrently monitor degradation happenings.

While optical sensors could be adopted to ascertain forest degradation triggered by wildfires and selective logging, plus an estimate of affected area extents (Asner et al. 2005; Souza et al. 2005; Herold et al. 2011; Morton et al. 2011; Kissinger et al. 2012), they can only sense variations that influence canopy properties, consequently ignoring understory variations. It is important to mention that forest degradation can be enigmatic both to field observation and RS procedures (Peres et al. 2006; Barlow et al. 2010; Berenguer et al. 2014; Mercedes et al. 2016). The hitches of sensing the occurrence of forest degradation under the canopy using satellite data have been generally acknowledged (GOFC-GOLD 2013; Bustamante et al. 2016).

In addition, proximate factors related to forest degradation can be assessed using binary logistic regression that is spatially explicit (Morales-Barquero et al. 2015; Kumar et al. 2019c). Arithmetical models are beneficial in determining the comparative significance and connection of possible proxies of forest degradation (Morales-Barquero et al. 2015). Socio-economic survey is also an important method for assessing the causes of forest degradation as it helps in defining the drivers as well as identifying appropriate interventions to be introduced (Inoue 1992; Nagata et al. 1994).

2.4 Drivers of Forest Degradation

Forest degradation is caused by a group of agents (drivers), with larger or less significant degrees of poorly measured connection between agents or with deforestation events (Matricardi et al. 2020). The drivers (sources) of forest degradation (Table 2.2) are complex (Acharya et al. 2011), vary at regional level, change over time (Boucher et al. 2011; Kissinger et al. 2012) and generally categorised into proximate, underlying and natural drivers (Fig. 2.1) (Acharya et al. 2011; Kissinger et al. 2012). These are numerous drivers, which are usually location-specific in nature, extending from policy and institutions to social and economic aspects (Houghton et al. 2000; Nepstad et al. 2001; Nkonya et al. 2013).

Several studies on forest degradation indicated that drivers such as timber extraction and logging activities (on commercial bases) are responsible for more than 70% of the total forest degradation in sub-tropical Asia and Latin America, while charcoal

Table 2.2 Direct drivers of forest degradation and their underlying factors (Adopted from Kaimowitz and Angelsen 1998; Nepstad et al. 2001; Nkonya et al. 2013; Chan and Sasaki 2014; Ty et al. 2011; Matricardi et al. 2020)

Drivers	Description	Underlying factors
Timber logging	Selective, legal and illegal logging	Livelihood, Sociodemographic, Market-driven
Extraction	Non-timber and forest products, charcoal production, fuelwood, hunting	Livelihood, Sociodemographic, Market-driven
Forest fires	Bush burning, understory fires, uncontrolled fires and all other types of wildfire	Production factors constraint, policies and governance issues
Land encroachment	Conversion to cropland and settlements, forest encroachment, shifting cultivation, forest fragmentation, forest clearing for large agricultural plantation	Livelihood, sociodemographic, production factors constraint
Free grazing	Livestock grazing in forests (both on small and large scale), cattle grazing	Livelihood, sociodemographic, policies and governance issues
Concessions	Large economic land concessions, timber concession	Policies and governance issues

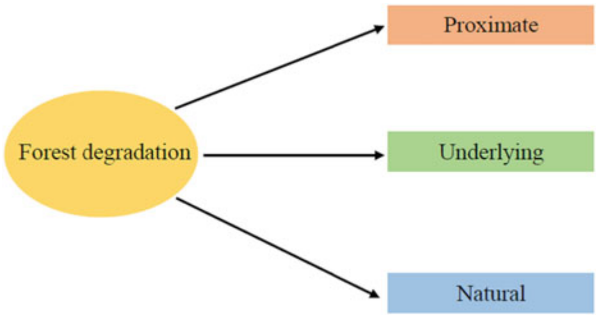

Fig. 2.1 Drivers of forest degradation

production, fuelwood collection and livestock grazing within forests are the key agents of degradation in most parts of Asia (Kumar and Singh 2020; Kumar et al. 2021b) and Africa (Acharya et al. 2011; Kissinger et al. 2012). The patterns of forest degradation agents are quite similar in Latin America and Asia (Hosonuma et al. 2012).

2.4.1 Proximate Drivers

The proximate drivers, also known as direct drivers are termed as anthropogenic activities or instantaneous actions that directly influence forest cover and carbon losses. They include over-extraction, targeting of high-quality commercial tree species, illegal logging, selective logging, forest fire, free grazing, fuelwood collection, charcoal production, forest encroachment, illegal settlement, invasion and colonisation by alien species, shifting cultivation and forest fragmentation (Matricardi et al. 2020). Anthropogenic disruption destroys forests via the destabilisation forest ecosystems, recovery prevention, ecological redundancy and reduction of taxonomic and functional diversity (Thompson et al. 2009; Kissinger et al. 2012).

2.4.1.1 Timber Extraction and Logging

The demand for wood (in form of timbers or logs) as materials for housing have intensely increased because of increased population growth, and it has led to overexploitation and degradation of the forests (Chan and Sasaki 2014). Commercial logging frequently affects or leads to forest degradation particularly in the tropical dry forests (Sanchez-Azofeifa and Portillo-Quintero 2011). Timber extraction and logging is the most prominent driver (of all the drivers) of forest degradation in Latin American and Asian continents accounting for more than 70% (Hosonuma et al. 2012). Selective logging was identified as one of the drivers of forest degradation in Eastern Amazonia (Berenguer et al. 2014). The extraction of commercial wood is the major driver of forest degradation in all continents barring Africa (Hosonuma et al. 2012). A study conducted by Chan and Sasaki (2014), inferred illegal logging as the most serious driver of forest degradation.

2.4.1.2 Extraction

Extraction in form of fuelwood collection, charcoal production and collection of NTFPs from the forests greatly enhances forest degradation. Charcoal and firewood generally serve as an energy source for rural communities, while NTFPs provide life support in terms of generating income and supplying products for domestic use. Over-harvesting and illegal logging of forests have resulted in forest degradation as a result of increased demand for wood energy (fuelwood and charcoal) (Belem et al. 2011; Etongo Bau Daniel 2016). Due to the unavailability of alternative sources of energy, a large section of the rural population relies on fuelwood for cooking, and thus, the pressure on the forests for fuelwood collection sustains (Chan and Sasaki 2014). The main driver of forest degradation in the continent of Africa is fuelwood collection and the production of charcoal as a source of energy (Hosonuma et al. 2012), with a lesser extent throughout Asia and Latin America.

2.4.1.3 Forest Fire

Forest fires act in response to forest structure, drought and fragmentation, generating distinctive degradation spatial processes (Bustamante et al. 2016). It releases CH_4, N_2O, ozone precursors and aerosols. It also has a wide range of impacts on carbon storage, forest structure and biodiversity (Barlow and Peres 2008; Geist and Lambin 2002; Silveira et al. 2013; Oliveiras et al. 2014; Etongo Bau Daniel 2016). It affects large areas of forests in the tropics (Morton et al. 2013), which has led to degradation. Forest degradation triggered by forest fires gives rise to significant amounts of non-CO_2 greenhouse gases (Bustamante et al. 2016). Multiple fire-induced forest degradation results in overwhelming effects on both biodiversity and forest biomass (Barlow and Peres 2004; Alencar et al. 2011; Morton et al. 2013). In Eastern Amazonia, understory fires were identified as driver of forest degradation (Berenguer et al. 2014). Uncontrolled forest fires are most conspicuous in Latin America (Hosonuma et al. 2012).

2.4.1.4 Land Encroachment

Conversion of forest land for settlement and agricultural activities such as shifting cultivation and other farming activities often lead to the degradation of the forest. Due to rapid population progression and quick economic expansion, particularly in tropical nations few decades ago, forest degradation has increased due to overexploitation or forest removal for resettlement and agricultural development (Kaimowitz and Angelsen 1998; FAO 2003). Most rural populations depend on forest resources for their means of support predominantly through shifting cultivation (Saikia 2014).

Shifting cultivation as defined by Mertz (2009) includes subsistence farming, slash-and-burn agriculture and swidden cultivation, and is considered a driver of forest degradation because of its cycle of operation. It entails forest clearing and regrowth, resulting in a landscape associated with low biomass density yet still qualifies as a forest (Houghton 2012). Forest areas with flatter areas in terms of elevation have greater probability of being used for shifting farming and higher probability of degradation (Becknell et al. 2012; Newton and Echeverria 2014; Morales-Barquero et al. 2015). Shifting farming creates complex mosaics of cover that may either lose or gain forest carbon reserves in any given area (Mertz et al. 2012).

2.4.1.5 Free Grazing

Livestock management within the forest is positively associated with forest degradation (Morales-Barquero et al. 2015). Cattle grazing often affects the composition and structure of forest, especially in the tropical dry forest (Sanchez-Azofeifa and Portillo-Quintero 2011).

2.4.2 Underlying Factors

Underlying factors are generally considered as the indirect drivers of forest degradation. They are intricate relations of social, economic, political, cultural and technological procedures influencing proximate drivers to cause forest degradation (Geist and Lambin 2002; Kissinger et al. 2012). From an institutional, economical and policy perspective, they are more complex (Mirzabaev et al. 2015). These elements act at multiple scales (such as international, national and local). International in terms of markets and commodity prices; national in terms of population growth, domestic markets, national policies and governance and local in terms of subsistence and poverty (Geist and Lambin 2001, 2002; Obersteiner et al. 2009; Acharya et al. 2011 Kissinger et al. 2012; Duguma et al. 2019). Indirect drivers include livelihood, market failure, sociodemographic, unplanned development, policies and governance issues (such as weak tenure rights, policy failure and capacity gaps), production factors constraint and market force (Acharya et al. 2011; Kissinger et al. 2012).

2.4.2.1 Livelihood

This is primarily tied to poverty and subsistence needs of local communities, such as forest cutting for new farms or agricultural extension, fuelwood collection and NTFP gathering for income. A lot of people rely on forest land and forest resources for their means of support to provide fuelwood, charcoal, house-building materials, fence posts and non-timber forest products (Maass and Balvanera 2005; Sunderlin et al. 2008). Several studies have found that forest products constitute an important and primary source of income for villages (Acharya et al. 2011; Chan and Sasaki 2014; Kumar et al. 2020) by providing both subsistence and cash income, having a resultant effect on the forest with evidence of forest degradation. A higher poverty rate supports the range and rate of degradation of forests (Chakravarty et al. 2012).

2.4.2.2 Market-Driven or Market Force

Demand for lumber, charcoal and other non-timber forest products (NTFPs) contributes to forest degradation. Rapid population growth and long-term dependence on forest resources for energy are major factors in the growth of the forest-product sector (Rademaekers et al. 2010). In a globalizing economy, economic growth based on primary commodity exports and rising demand for timber and other forest products are significant indirect drivers. It is destructive to the forest when charcoal is extracted or harvested without permission, which is mostly motivated by the requirements of urban and peri-urban people who live near the forest. Furthermore, the demands from increasing adjacent metropolitan and peri-urban regions routinely boost the marketing prospects for wood products, prompting local communities to engage in the extraction of wood from forests for sale.

2.4.2.3 Sociodemographic

The growing population (in rural, urban and peri-urban area); migration (to areas adjacent to forest) and significant expansion of settlement or residential area have all contributed to an increase in demand for forest products, particularly wood, which is required for construction and energy. The most generally reported underlying factor of forest degradation is population increase (Kissinger et al. 2012). A growing population suggests rising demand for forest goods (Rademaekers et al. 2010; Khuc et al. 2018). Rapid population growth in forest areas frequently leads to forest encroachment for settlements, a rise in demand for land for food production, forest products (such as poles) as construction materials and fuelwood for household energy consumption (Duguma and Hager 2010; Rademaekers et al. 2010).

Unfortunately, limitations such as limited access to substitute energy materials (e.g., electricity and solar panels) and alternative non-wood construction materials (e.g., concrete and steel) force ever-increasing populations to rely primarily on surrounding forests for both energy and construction. According to Duguma and Hager (2010), at least 39 per cent of the wood used to construct rural dwelling units came from natural forests. The expanding population's infrastructure demands, as a result of the rise of urban and peri-urban areas, have continued to increase the pressure on forests for construction timber extraction (Duguma and Hager 2010). The ratio of forest area to population size and the degree of social marginalisation of each community within and around a forest are positively linked with how likely it is that forest degradation will take place (Morales-Barquero et al. 2015).

2.4.2.4 Production Factors Constraint

Land scarcity for agriculture and urbanisation, as well as low land productivity, all contribute significantly to forest degradation. There are numerous human activities, including rapid population expansion, fighting for the same relatively fixed area. As a result, new immigrants destroy neighbouring forests for agricultural purposes and housing construction. Farmers, particularly those in rural areas, who cannot afford commercial fertilisers for their soils, used agricultural waste for cooking and heating (Duguma et al. 2014). Furthermore, the deterioration of soil fertility on most agricultural lands, resulting in low productivity, drives farmers to destroy forests for cultivation or alternative sources of income. Forest soils are recognised to be fertile and productive for agriculture.

2.4.2.5 Policies and Governance Issues

Unstable and changing policies, policy failure, weak law implementation, irregular and ambiguous land allocation practices, weak forest sector governance and failed institutions, a lack of resources in public forestry organisations, weak tenure rights, attitudinal and habit factors, corruption, poor governance, political instability and insufficient natural resource organisation and monitoring are all essential underlying factors driving forest degradation. According to a report by Kissinger et al. (2012), 93% of nations have recognised inadequate forest sector administration and institutions, illegal activities (mainly because of taxation) and contradictory policies outside the forest sector as important underlying causes of forest degradation at the national level.

Changes in policies result in changes in forest management methods or approaches over time. These management practices can sometimes be unjust to communities living in and around woods. For example, relocating forest people or settlers to non-forest regions without sufficient consultation or need assessment. People who have been moved are often unwilling to provide their agreement because they believe that relocation is unneeded and hostile, and thus fails to protect forest exploitation. The illegal logging is aggravated by the relocation (Duguma et al. 2019).

Ineffective policies aggravate forest degradation due to the failure to include and discuss all essential stakeholders, especially local communities, during policy formation. Policy failure also creates strong sense of resentment between government forest services and communities (both within and surrounding the forest). Furthermore, some of these policies usually lead to loss of land by the communities and as a result of that, negative views and opinions (which are the bases for attitude and habits) are formed. Most communities feel deprived, neglected and marginalised by the respective governments and therefore drive illegal exploitation and extraction of forest products at any possible chance.

In addition, irregular and unclear land allocation practice regarding land and timber concessions is another factor that drives forest degradation. Part of forest land and products are often lost or damaged when concessions areas are extended beyond their officially allotted areas into the forest and areas surrounding the forest. Failed institutions together with weak forest sector governance also play a vital role in driving and completing of forest degradation drivers. For instance, when forest institutions are not strengthened enough (through capacity building, provision of funds, motivation, etc.), then they become too weak to discharge their responsibilities. Communities within and around the forest would possibly capitalise on that by engaging in illegal exploitation. Also, corrupt practices, illegal activity (related to weak enforcement) and lack of cross-sectoral coordination among the forest officers critically drive forest degradation. For example, Kenya had the highest natural forest loss due to corrupt practices of forestry officials between 1972 and 1990 (Ndungu Land Commission 2004; Wass 1995).

2.4.2.6 Natural Drivers

Natural drivers are generally considered to be exogenous and overwhelming (Acharya et al. 2011). Natural drivers include natural disturbances such as windstorms, drought, etc. Windstorms, particularly when associated with forest disintegration and fire have been shown to drive forest degradation (Bustamante et al. 2016). Windstorms and other wind-related disturbances can initiate considerable losses in forest biomass (Negrón-Juárez et al. 2010; Espírito-Santo et al. 2014) and fragmented lands (Benchimol and Peres 2015). It is important to mention that policy instruments would not help to control them.

2.5 Conclusion

To summarise, it can be said that forest degradation is a significant disturbance of the forest ecosystem. Among all indicators, biomass loss is the most common and prominent one. Degradation is influenced by local, underlying and natural factors.

These factors are often multiplex and location-specific in nature, acting at manifold scales. Logging and forest resource exploitation, fires, land encroachment and free-grazing, as well as other variables such as livelihoods and sociodemographic and market dynamics are all aspects that contribute to the problem of forest degradation. A variety of approaches as discussed earlier can be used to correctly measure, monitor and evaluate the extent and magnitude of forest degradation. The events of forest degradation can be effectively assessed through a combination of different approaches.

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The So-called Modern 'Sustainable Forestry' Destroys Wilderness, Old-Growth Forest Landscapes and Ecological Services Worldwide: A Short First-Hand Review and Global Narrative on the Use of 'Growth-and-Yield' as a Destructive and Even Impossible Goal

3

Falk Huettmann and Brian D. Young

Abstract

Old-growth forest wilderness areas are on a rapid global decline. Science-based sustainable forest management (SFM) is practised worldwide but here we show with ground-truthed examples across the world that it is not sustainable on a finite landmass: it encroaches in wilderness areas, employs a road network, has a negative energy budget, makes landscape-scale vegetation younger, and destroys old-growth forests, besides other impacts. The 'modern' concept of managed forests and promoted tree plantations to sequester carbon and to quickly produce timber is presented in a meta-analysis from over 15 nations and first-hand accounts by the authors as standing in full conflict with the promotion and welfare of old-growth forest wilderness and all their ecological services on a finite planet. Policies and concepts are exposed that are used by agencies, institutions and NGOs to promote managed neoliberal forests, tree plantations, but that are

'Tibetan Buddhists and followers of the Bon faith see the universe as interconnected and interdependent. Industrial activities like forestry, freshwater fisheries, mining and damming on their ancestral lands are perceived as gross interference with Mother Nature—and disturbing powerful spirits thought to dwell in the earth and on mountain-tops, and in rivers and lakes.' Michael Buckley, editor of *This Fragile Planet: His Holiness the Dalai Lama on Environment.*

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harming the ancient forested wilderness landscapes and their associated human cultures and societies as well as the atmosphere and global well-being.

Keywords

Old-growth forest · Sustainable forest management · Biodiversity · Habitat loss · Global change · Yield table

3.1 Introduction

Sustainable forest management (SFM) is practised worldwide but is not really sustainable (Brandt et al. 2016). The difficulties are compounded by the desire to meet present and future competing demands on forests while conserving important natural resources. While the term 'SFM' has been widely accepted (Charron 2005), a clear singular and meaningful definition has actually been elusive (Wang 2004). But, it can be generally thought of as a triad of balancing ecological, social and economic values to meet society's objectives over the long term (Sheppard 2005; compare with Daley and Farley 2010). However, in such forest management schemes, the actual forest structure and even timber volume remain unaccounted for in precise, scientific and relevant terms. What some in the forest management community consider a simple concept (Von Gadow 2001), SFM involves a very challenging task of developing and implementing management strategies, environmental commitments and policies on a landscape scale and across international boundaries, agencies and cultures. Already the inclusion of fire shows a clear conundrum (e.g. Bergeron et al. 2004). All of this management must occur on a finite landmass to meet emerging social needs and global trends while at the same time accounting for all the legacy and ongoing ecological impacts of a logging industry that has a sole desire of 'getting the wood out'.

Those issues of sustainable forests and their management are not really new, but it has taken on a new meaning and urgency in recent decades (Burton et al. 2003). The roots of the 'western' SFM extend back to at least 1346 when King Philippe of France decreed that forests are to be continuously maintained and kept in good condition (Forestry 2012). Locally, SFM was promoted even earlier, for instance in Austrian salt mines that needed a consistent wood supply for their production process with steam. However, it was not until recently that SFM became globally recognized due in part by changes in societal values towards sustainable development that were highlighted in the Brundtland report 'Our Common Future' (Brundtland 1987). Keeping its colonial top-down approach, it is now enforced with the UN Sustainable Development Goals (SDGs; https://sdgs.un.org/).

In recent years to implement SFM, an adaptive management (AM) framework has also been applied (Holling 1978; Foster et al. 2010). The linking of SFM and AM has created adaptive forest management (AFM) which aims to preserve and develop the functionality of forests as a prerequisite for fulfiling the future need for forest ecosystem services (Wagner 2004; Kumar and Singh 2020; Kumar et al. 2021). AFM based in the broader framework of ecological forestry, which is based on four foundational principles of (1) continuity, (2) complexity, (3) timing and (4) context, serves as a hopeful path forward to help revitalize forests (Franklin and Johnson 2013). Sadly, these methods are largely not practised outside of a few research and demonstration plots (Nagel et al. 2017), and as will be assessed below, the 'modern' practices widely fail on old-growth forests (see Rich 2013).

Many definitions of sustainability exist (Von Gadow 2001; Wang 2004); modern forestry—it usually started after the world war 2—tends to be based at least on the concept that not more should be taken than what re-grows, and thus, overcutting is avoided, and forested landscapes stay in a sustainable 'status quo' and in good health. This is meant to be valid for next generations, if not even indefinite. Forest inventories, as done by plots or remote sensing are used involving databases and growth-yield computer models to obtain sustainable harvest rates. By now, such a modern forestry enterprise is widely institutionalized worldwide—essentially every nation has it (see Buscher and Fletcher 2020 for Non-Governmental Organizations NGOs). It involves science, academic institutions and education to achieve such and similar goals in the public eye based on a public trust resource.

At the core of the annual forest re-growth estimation for a sustainable 'take' sits forest inventory and the growth-and-yield table, specifying how much wood can be taken every year in an area without harming its forest volume (Von Gadow 2001). In that approach though, structural and qualitative forest aspects—as well as wider landscape, connectivity, holistic and long-term sustainability perspectives—remain widely excluded and thus unresolved. Already just considering the large national and international imports and exports of timber and processed wood products in the 'modern' global economy (Dudley et al. 1995; Rich 2013), it is not clear how a balance between harvest and re-growth is truly achieved for sustainability. That is because growth-and-yield tables just express timber volume locally and in a very reductionist subsampled, hardlrepresentative fashion (a stand scale, at best; most growth-and-yield tables are actually based on a few very well measured trees and species over time, e.g. North American Sylvics textbook) (https://www.srs.fs.usda.gov/pubs/misc/ag_654/table_of_contents.htm). They essentially lack updated and publically available landscape-scale inference for this public trust resource.

For biological authenticity, such growth curves need to be based instead on at least one full forest rotation period (in nature, that can easily mean more than 200 years and a landscape scale, but such scientific data do hardly exist in most parts of the world, nor are they readily available and shared, e.g. when of commercial and strategic value). Such growth-and-yield tables need to be understood in a complex and ever-changing environment, e.g. nutrient contamination, water table changes and climate change (CO_2 concentration). While recognizing that atmospheric metrics and criteria are for instance on the rise in forestry management for inclusion, the forestry discipline and its tools still struggle with such concepts, e.g. air contamination and fertilization by NO_X, in REDD and REDD+ (https://www.un-redd.org/; see Schmid et al. 2015 for an application in Central America). At the core of such questions still sits the driving economic framework, while relevant old-growth forest attributes including wilderness and remoteness play virtually no value nor are they fully quantifiable or really inventoried yet, or even part of most forest sciences (see Wagner 2004; Wohlleben 2016; Simard 2021 for assessment and real-world professional experience).

In the construction of yield tables for trees and forests, stand growth patterns and management scenarios are assumed; as are the assumptions in knowing all tree species' taxonomies and all possible interactions. Any deviation from these assumed patterns which are typically found in old-growth forests—or a management scenario - will result in completely different stand characteristics and a complete mismatch with growth-and-yield tables. Comparisons between growth-and-yield results and actual stand dynamics are normally not as meaningful as researchers would like because it is inevitable that the growth of an individual stand will vary in some way from the patterns assumed in a yield table. It is worthwhile to mention that those long-term yield tables initially come from an environment that is very different from what we have now and what is to come. 'Simply' correcting those is almost not possible in complex ecological settings.

Clearly, the original (old-growth) forest ecosystem is not renewable because one cannot simply fix or recreate—'build' (Von Gadow 2001; Wagner 2004), an old-growth forest ecosystem in less than two centuries on a landscape scale. Nor is it even clear what to build such a forest for? Old-growth forests serve many goals and are simply too complex to be built and re-created by humans; they provide many ecological services that are not fully understood yet but important to people (e.g. clean water and air, recreation, maintaining biodiversity, spiritual values, telecoupling (Liu et al. 2018), etc.). Size matters: Today, very few old-growth forests remain that are even large enough in a scale to be functional, self-sufficient and resilient ecosystems (e.g. DellaSala 2011; Schoen 2021).

In the meantime, modern nations and their institutions are widely out of resources and wildly in debt (Rich 2013) and thus, they engage in a heavily economic market-driven global model of forestry, to be more self-reliant, or to give the impression that they are trying to be. It appears to be well carried by the public to sustain themselves and gain a better standing within their respective administrative systems and competing ministries. This model of forestry puts the creation of money at the forefront, and it puts pressure on any space and untouched area left for such timber production schemes. Leadership consists of more than balancing budgets though. As 'time is money' in the modern world, the best-possible timber is produced and processed as fast as possible to bring it to the market for consumption, any consumption, including plastic-enforced timber and biofuel (Fargione et al. 2010). Waiting for +300 is discriminated against. While this is achieved through rapid-growth plantations near road systems, genetically modified and optimized, pruned, thinned and fertilized trees as well as full-harvesting and saw mill operations—computer-aided—it does that on the actual cost of old-growth forest and remote wilderness. Such timber production is on the rise worldwide (Victor and Asubel 2000; Rudel 2009), in the same time ancient and remote old-growth forest wilderness habitats in their respective ecosystems, their species, areas and ecological services are

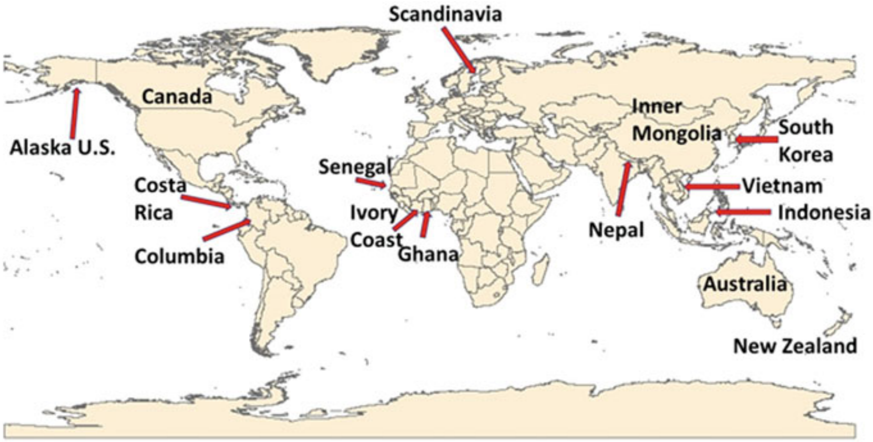

Fig. 3.1 A selection of global examples where the promotion of tree plantations stands in direct conflict with old-growth forests and eliminates those wilderness landscapes for no meaningful and justifiable reason

disappearing. The negative correlation between those two trends is obvious as it happens on a finite and competing space, globally (Daley and Farley 2010). These concepts stand in direct contrast and are mutually exclusive (Czech 2002).

The impacts of climate change affect plant physiology and this forest function and productivity, (Kumar et al. 2019a). However, climate change also has an indirect impact on ecosystems (Rawat et al. 2020; Kalra and Kumar 2018; Kumar et al. 2018, 2020). It is done through changes in the composition and diversity of plant communities. Modern forestry—as practised globally—also tends to manage diversity (Kumar et al. 2019b). Typical examples are found in teak plantations of tropical rainforests in Central America (where often easily over 300 species can origially be found on a few hectares while teak is an introduced singular species there (Huettmann 2015a, b and references within)). Losing key species reduces the strength of the diversity-productivity relationship more severely in environments that are becoming climatically harsher. Ecological forest management has been proposed and implemented as a method to enhance forest structure and composition, but these practices are still only marginally practised, hardly well defined. Widely promoted and applied, the concept of fast-growing tree plantations (see Greenpeace Nordic and Protect the Forest Sweden 2021) for Sweden as a claimed global success model widely ignores though the old-growth forest concept on a global scale. This will arguably change the face of the earth forever, as wilderness re-naturalization is becoming extinct (see Allen 2003 for Coast Rica), ecological services are decaying, the evolutionary process is interfered with and the atmosphere is harmed further.

In the following, we will provide several examples around the world (Fig. 3.1) where this problem already has occurred and where it is exacerbated and where the authors have witnessed it first-hand. For authenticity and evidence, we outline it at the end of each national example. Instead of a research experiment, these examples are to be seen as a meta-analysis to show the evidence.

3.2 National Examples

3.2.1 Columbia

Columbia is a tropical nation with much prime forest left, namely in the Caribbean, Andean and Amazonian ecosystems. Many of those forests are of world fame but are now widely on the decline. The indigenous people in those regions are heavily affected, and partly, pushed out, beyond the earlier colonialization by European nations. In addition, mining and resource extractions, including warfare, add to those conflicts and to a different land-use. In the meantime, Columbia has received a lot of support and subsidies from The World Bank and the international community, e.g. to join international markets and to plant and regrow forests on a nation-wide scale, specifically with fast-growing plantations. A good example of the link between the global economy and modern-day politics can be seen here:

> '*At the end of January this year, Colombian President Iván Duque announced at the World Economic Forum held in Davos, Switzerland, that the country's goal is to plant 180 million trees by 2022. This is based on the restoration of more than 300,000 hectares (741,316 acres) of degraded land.*' (Mongabay 2020)

These problems in Columbia were seen first-hand by FH (author), e.g. in the wider Andean region; more details were found with Huettmann (2015a, b, c, d, e) for the Caribbean region.

3.2.2 Côte d'Ivoire

Côte d'Ivoire located in West Africa was formally ruled by the colonial powers of France. Since independence in 1960, the development of cocoa production for export, and foreign investment have made Cote d'Ivoire one of the most prosperous nations in West Africa. It is part of Francafrique, a fascinating political phenomenon: the continuous subjugation of supposedly sovereign African states by their former colonial master in terms of a de facto 'colonial tax' (Diop 2018). Forestry-wise, a strong north-south gradient exists which is characterized by the Guineo-Congolian rainforest region along the southern coast, a narrow Guinean region composed of seasonal wet dry deciduous and semi-deciduous forests and the Sudanian dense woody savanna that borders Bukina Faso in the north CILSS (2016). These ecosystems offer unique and rather rich species biodiversity. However, the formerly massive rainforest is now reduced to small pockets of forest remnants, mostly centred on the Tai National Park (e.g. Oates 1999). Beyond Francafrique, the nation of Côte d'Ivoire and its resources are heavily affected by civil warfare and conflict, adding to its ongoing poverty problem. Over the same period, Côte d'Ivoire has received major support to grow cocoa and nuts, all based on plantations in its tropical belt. This nation is likely the largest producer of raw chocolate. Arguably this goes on the cost of the former rainforest habitat, its soil and social factors, e.g. child labour. These plantations come with a strong (western style) business model and are often approved by agency agro economists and western-world consumers wiping out old-growth vegetation (Tondoh et al. 2015; Pearce 2019).

These situations have been witnessed by the authors in person for the rainforest of the Tai region, Grand Bassam nut and cocoa plantations, as well as tree plantations further north. Notable are the massive forest cuts from the 1970s and agricultural transitions of the initial rainforest.

3.2.3 Senegal

Senegal has a very similar colonial history to that of Côte d'Ivoire and is also part of Francafrique but, fortunately, Senegal is among Africa's most stable countries, with three major peaceful political transitions since independence in 1960. While part of the Sahara belt, Senegal has about 45% of the country forested with the northern half of the country in the Sahelian region, comprised of short grass savanna with thorny trees particularly from the genus Acacia, and the southern half in the Sudanian region with a range from sparse to dense woodlands CILSS (2016). About 18% of the forest is still classified as 'old growth'; however, the number is decreasing annually. The largest driver of forest loss is a result of agricultural expansion and is having a profound impact on the landscape due to forest fragmentation and the erosion of the remaining natural ecosystems. While not at the same scale as agricultural expansion, deforestation resulting from clearing for fuelwood use, charcoal production and logging all have significant impacts on ecosystem structure and function. In the same time, Senegal does receive tree plantation support, e.g. to fix soil and increase forest coverage (Afrik21 2020). A typical quote from this source is provided here:

> '*The Senegalese government is determined to succeed in its new reforestation campaign in aiming to plant 20 million trees across the country before the end of September 2020.*'

Of specific interest in this campaign is the baobab tree (*Adansonia* sp.), which is part of the initial vegetation cover and can get easily over a 100 years old but which forests are not restored well over the coming generation and with mass plantations.

The Decentralization Law of 1996 in Senegal transferred natural resource management from the government to local communities but the actual ownership of these forests is still held by the centralized government (FAO 2005). This public ownership could be one of the drivers of deforestation due to the Denice of the local communities that they are not responsible for these lands. Of the 8.7 million ha of forest land, 60% is designed for production and only 18% is slatted for protection or conservation (FAO 2005). These situations across the county have been witnessed in person by BDY (author).

3.2.4 Ghana

Ghana has a similar history and set up like Côte d'Ivoire, but Ghana is a former British Colony and did not pay the 'colonial tax'. While several military coups have occurred, Ghana is more stable than Côte d'Ivoire. Ghana followed the western rules, e.g. the Washington Consensus (https://www.britannica.com/topic/Washington-consensus) and the subsequent Ghana Economic Transformation Project (GETP), and thus it received more aid money. This aid money has resulted—in part—into forestry support, as well as plantations and hydro dams, e.g. the large Volta Dam (Akosomba Dam) for the aluminium industry modifying that entire water table and estuary forests. Overall, the modernization has changed Ghana's natural ecosystem into a more managed ecosystem on a grand scale, as wanted by The World Bank, International Development Agency (IDA) and other donors. As a net effect, the original forest vegetation is heavily reduced and ancient landscapes disappeared, planted trees dominate instead of the traditional forest vegetation and landscapes.

These situations have been seen by the authors in person for the hydro dam Volta watershed, the capital city (located in the ancient rainforest belt) and many coastal former rainforest habitats and drier steppes north.

3.2.5 New Zealand

New Zealand is a relatively rich island nation and a dominion in the British Empire. It was free of humans until the Polynesians arrived, and the human footprint increased further when James Cook 'discovered' 1769 New Zealand bringing a western-style civilization and such forestry. New Zealand had many old-growth forest landscapes but which have now vanished, while plantations are on the rise, as promoted by modern forestry and their departments. The ancient forests in the mountains have disappeared, as the old-growth forests in coastal areas making space for tree plantations instead. These situations have been seen by FH for the southern island and riparian forests.

3.2.6 Australia

Australia is an isolated landmass and it is largely described by its large interior dry areas (outback), but some lush coastal belt regions, e.g. tropical north and southeast, including Tasmania. The latter regions have been old-growth forests for millennia (see Lines 1999 for description of tree removal with a 'modern' civilization). Native eucalyptus forests are an inherent part of this discussion. But many are now just plantations of highly-bred eucalyptus. In recent times, tree removal and tree plantations, also large landscape fires due to dryness, e.g. mitigation and climate change, resulted into a generic and large loss of the original vegetation. See Williams et al. (2003) for climate change effects in remote mountain areas; Koch and Munks (2018) for the Tasmania old-growth forest 'conflict'. In the Australian Northeast, sugar cane plantations further add to forest loss. The ancient and continous forest canopy of the Northern Table Lands is widely lost. For Tasmania and Australian coastal zones like the northeast, southeast and southwest, FH was able to observe the loss of old-growth forests and the rise and dominance of general tree and sugar cane plantations.

3.2.7 Costa Rica

Costa Rica presents itself as the poster child of rainforests, biodiversity and conservation (https://costarica.org/vacations/custom). However, the actual destruction of the rainforest is on a record high, while Coast Rica is largely in debt (one of the highest debt rates in Central America, Huettmann 2015a, b, c, d, e), and tree plantations are rising, e.g. introduced teak and eucalyptus. Many of those plantations are funded by outside donors/NGOs and they are part of certified product schemes, e.g. locked up land set aside for an otherwise industrial banana and pineapple production for the export market using insecticides, cheap labour, etc. replacing tropical rainforests (Huettmann 2015b). Overall, Costa Rica has major modern forestry and agroforestry schemes, including shade-grown coffee e.g. based on non-native trees), but none really promote or produce old-growth forests. The latter are on a large and ongoing decline for many decades already (e.g. Huettmann 2015a, b, c, d, e). Compared to the earlier coverage, only a few widely celebrated blocks of such rainforests are left, e.g. in national parks which receive an acclaimed PR (e.g. GoVisit Costa Rica 2020). These situations of changing old-growth forest areas towards certified and even fenced invasive tree plantations are well known and, in part, studied and documented by FH for many years (e.g. Huettmann 2015a, c, d).

3.2.8 Scandinavia (Norway, Sweden, Finland)

The 'Scandinavian Forestry' model is following the initial Central European concept of forestry and sustainability. It traditionally provides for the Central European market, e.g. timber and pulp and paper (the latter produced according to standards that are not all necessary compliants with the mainland EU ones). While clearcutting was stopped relatively early, an extensive road network was still needed and has been established throughout Scandinavian forests allowing for a harvest and second harvest (Greenpeace Nordic and Protect the Forest Sweden 2021). Companies like IKEA became a globalization hit, making use of such forestry schemes, now internationally and continuing with other timber sources abroad. Their timber demand can hardly be met by Scandinavian forests alone and uses timber from abroad. In recent times, the Scandinavian forestry model also strongly aims to sequester carbon (https://www.straitstimes.com/world/europe/cutting-down-trees-can-help-save-climate-in-forest-industry-math). That is done through fast-growing tree plantations with record short-term rotation periods (compare with Old Spruces of 900 years old; https://en.wikipedia.org/wiki/Old_Tjikko; Wohlleben 2016 Simard 2021). Arguably, such forestry runs on the cost of the initial old-growth forests and their area. As a matter of fact, old-growth forests achieve equal or better carbon sequestration, but such wilderness areas are on the decline and by now make up just a tiny fraction of the forest land in Scandinavia, while the adjacent Russian forests for instance—in the same ecosystem adjacent to Scandinavia—can easily show a rather different structure. Many species now endangered in Scandinavian forests are still quite common on the Russian side, e.g. white-backed woodpecker (*Dendrocopos leucotos*).

The authors have seen the described situations in Scandinavia (Norway, Sweden and Finland), and comparable Russian (Kyrelian) forest landscapes, many times and first-hand.

3.2.9 Canada

Canada has a vast landscape that initially was covered with large tracts of old-growth forests, e.g. in the Pacific Northwest, rocky mountains and boreal forest. Those areas are of world fame and often part of the world's largest forests. However, Canada runs primarily a public land scheme, and the old-growth forest in the Pacific Northwest is now reduced in some instances to over 80%, e.g. on Vancouver Island. The boreal forests in Canada, e.g. Alberta, British Columbia, Labrador and Eastern Canada are considered to be highly industrial; they are dominated by clear-cuts, short-term tree plantations, and many species are on the decline, e.g. caribou (Brown et al. 2007, Hervieux et al. 2013). As a matter of fact, many valleys of coastal old-growth forests were fully cut out already. To this very day, large clear-cuts remain the method of choice for forest harvest in Canada. Canada had initially no relevant size or location constraint of clear-cuts, and later a loose policy of 'green up delays' was put into the forest practices code to at least create a better-looking but equally devastating clear-cut harvest (see also Charron 2005). For forest reproduction and replanted areas, many forests now have rotation periods of less than 100 years, which stand in stark contrast to old-growth forests that otherwise easily can get 350+ years old.

Canada has now started to protect some old-growth forests, e.g. the Great Bear Rainforest (Gonzales et al. 2003; Howlett et al. 2009), but much of the forest that has been conserved is of lower quality than the original old-growth forests that were harvested (see previous references for details and disputes).

In the Yukon territories, the annual allowable cut is based on area control and the use of an inventory. Forests are then divided into site productivity rankings with the vast majority ranked low to poor. The small amount that is ranked well is then slated for harvest. So effectively, the highest quality timber which is also correlated with 'Old Growth' is being systematically removed from the landscape. This is similar to 'high grading' (a traditional destructive forestry practice employed in Eastern Canada since colonial times for white spruce for instance; e.g. Wynn 1974). Most of such timber is more than 200 years old and while planting does occur, the rotation period is slated at 100–120 years (at least an 80 year mis-match to stay even). This is virtually the same situation that occurs across the boreal region of North America including the interior of Alaska (see below).

The authors have extensive experience on many of those forestry issues; see also Yen et al. (2004), Huettmann et al. (2005) and Nielsen et al. (2008).

3.2.10 Alaska U.S.

Alaska is blessed with extensive forest cover and ecosystems such as the boreal forest and coastal old-growth forests. Tongass and Chugach are the largest temperate old-growth forests in the world; it is part of the North Pacific temperate rain forest that extends from northern California through Oregon, Washington, British Columbia up through southeast Alaska and to the Kenai Peninsula and Afognak Island. Tongass for instance is home to indigenous Tlingit and Haida people and supports a vast salmon run and associated large culture and society (Brinkhurst 2011). It has received a very intense forest road development scheme (e.g. Schoen 2021) and is considered by many, as substantially harvested. That is despite just a rather short history of industrial forestry that just began in the 1950s (compared with Europe or Asia where a forest cutting history of over 1000 years can be found), and a decline in the rate of harvest after the 1990s. However, the US Forest Service has recently planned to accelerate clearcutting of old growth on the Tongass, the only national forest that is still clearcutting old growth, which is now considered by scientists to be unsustainable. The Trump administration's exemption of the Tongass from the national Road less Rule will further high-grade the rarest, most valuable old growth across the Tongass (Orians and Schoen 2013; Schoen 2021).

In terms of Native corporation lands in SE Alaska, under ANCSA (Alaska Native Claims Settlement Act https://ancsaregional.com/about-ancsa/), the regional and village corporations selected some of the best quality old-growth forest lands across the Tongass and clear-cut them rapidly (not sustained yield forestry) to maximize short-term profits. Sealaska, the regional corporation, has liquidated much of its old growth and is now selling carbon credits for remaining forest lands; app at $100 million worth of credits so far are sold (see also Moomaw et al. 2019).

One of the key issues on the Tongass is that the large-tree old-growth habitat on the Tongass has always been rare but has been the target of logging for the last 70 years. Thus, although there is still, technically, a lot of old growth left on the Tongass, the best stands (and most important fish and wildlife habitat) have essentially been high-graded and it is now at least half as abundant as it was prior to industrial logging (DellaSala 2011; Albert and Schoen 2013). As an example, the most productive timber area of all of Alaska occurs on northern Prince of Wales Island. Since 1954, the contiguous stands of high-volume old growth were reduced there by 94%.

For such forests and their so-called sustainable management, there actually exists an alternative to those forestry practices, and as promoted by the institutions: the Chugach Forest. Compared to the Tongass and Canada, the Chugach was always a low-quality timber producing region at the far northern extent of the range of the North Pacific temperate rainforest. Proportionately, there is much less high-quality old growth on the Chugach than there was on the Tongass and it was far from market. Native land selections under the ANCSA targeted much of the most valuable timber-producing lands and most of that have also been clear-cut. But for the last 20 years, the Chugach has been considered a fish and wildlife and recreational forest not a timber-producing forest. It simply was not cost-effective to have a big timber industry on the Chugach compared to the Tongass. Thus, it received less cutting and more protection. Consequently, it stands now in big contrast to most of the Tongass when it comes to percentage of wilderness, road-free areas, old growth and species (Morton and Huettmann 2018). The Chugach can be seen as a control site, now showing the mismanagement of the other ancient forests.

Another forest, the boreal forest in the interior of Alaska is part of 'the largest' connected forest in the world (Wurtz et al. 2006). The boreal forest of Alaska is the predominant ecoregion within the state. The vegetation within this forest type is comprised of a mosaic of stands of different ages and sizes represented by eight species, but a relevant species there is the white spruce (*Piceaglauca,* e.g. Ohse et al. 2009; Morimoto et al. 2016, 2017). In interior Alaska, where wildfire is the major source of forest disturbance (Lynch et al. 2002), management decisions directly affect the forest structure using different levels of fire suppression activities across the landscape (Haggstrom 2003).

In interior Alaska, there are approximately 9.6 million hectares of commercial forest land and an additional 33.2 million hectares of open woodland that could potentially be harvested or thinned to reduce hazardous fuel conditions (van Cleve et al. 1983; Angelstam and Bergman 2004; Wurtz et al. 2006; see Hanson 2013 for inventory of the Tanana Valley State Forest). But there is not a comprehensive sustainability plan for Alaska's boreal forest. Alaska prefers a concept called 'low-input management' (Morimoto et al. 2016, 2017). Still, the relative extent of forest removal in Alaska's boreal forest is relatively low compared to the Tongass or compared to some of the Canadian provinces.

While the United States is one of the chief lumber-producing and driving countries in the world (Houghton 2005; Wernick et al. 2008), interior Alaska is experiencing a growing portion of its timber harvests just being used as fuel. This increased interest in biofuels and other forms of bio-energy within Alaska is being driven by a combination of energy independence and high energy prices (Fresco and Chapin III 2009; S. Parnell pers com.). A few communities within Alaska are beginning to incorporate wood-fired energy systems utilizing cord wood, chips and wood pellets. Some of it is subsidized. While the scale of the current operations is small (from 10s to 100 s of hectares), the increased interest in biomass is unconstrained and will potentially impact thousands of hectares of forested lands annually (Forestry 2012).

The boreal forest of interior Alaska has received a lot of forestry activities over the last 120 years, namely 'high grading' for white spruce and clearcutting (Roessler 1997; Wurtz et al. 2006; Hanson 2013). This has happened in two bigger waves: with the gold mining rush around 1900s, and then, in the 1980s and 1990s related to the pipeline activities in Alaska, as well as in parallel with a brief but vigorous export market to Japan. Consequently, a vast network of winter use and year-round roads have been established over the last 120 years to allow for such a tree removal without much of a sustainability plan (see Hansen and Naughton 2013 for an example and impact assessment). A train system existed in the 1920s and 1930s in support of mining in the Tanana valley but it lost support and profitability when all relevant forest stands were cut out. In most cases, such a tree harvest is based on cut blocks (clear-cuts). Little coarse woody debris (CWD) is left over, and thus, depletion of carbon and nutrients is occurring. Due to the extreme growing conditions and low temperatures, the boreal forest has very slow growth rates. Thus far, there is limited immediate regrowth of white spruce (Morimoto et al. 2016, 2017) which can be alarming (an apparent re-growth only occurs in later decades).

To this very day, Alaska has no statewide and consistent forest inventory with public available geo-referencing (see Young et al. 2017, 2018), hardly a landscape-scale enforcement power. While strongly growing in Alaska due to the demand and increasing pressures and questions, the U.S.-wide gridded USDA Forest Inventory and Analysis (FIA) program has just been established in interior Alaska (starting in the summer of 2016). Like in most of the U.S., the FIA plots carry hardly geo-referencing information, e.g. latitude or longitude to be useful for site-based research (those locations are not exposed for privacy reasons). The only broad-scale permanent sample plots with repeated measures within the interior of Alaska are the CAFI and WAIN datasets (Malone et al. 2009; Rees, personal communication) as well as LTER (https://www.lter.uaf.edu/) and NEON (https://www.nsf.gov/news/special_reports/neon/about/). Although these data represent the largest compiled collection of information on forest dynamics in Boreal Alaska (Malone et al. 2009; Rees, personal communication), they are not uniformly dispersed across the region and can hardly be generalized or put to good use on a landscape scale. Their use for growth-and-yield tables is virtually impossible.

While growth-and-yield tables are widely missing in interior Alaska, several forest dynamic models have been developed using the CAFI and WAIN datasets (see Liang 2010; Liang and Zhou 2010; Liang et al. 2011; Young et al. 2011, 2017, 2018). In addition, a forest inventory has been conducted on all 'State of Alaska' classified forest lands (see Alaska Division of Forestry, Alaska statewide forest inventory retrieved on April 13, 2021, from https://forestrymaps-soa-dnr.hub.arcgis.com/). This one-time assessment has been used to establish an area control management plan (like what exists in the Yukon as highlighted above). The CAFI and WAIN datasets to date have not been incorporated into the state's forest management plans though, and thus, the inventory is static and does not consider any forest dynamics consisting of many gaps. Additionally, forestry operations occurring on State of Alaska lands do not have any policies that limit the maximum clear-cut size (see details in The Alaska Forest Resources and Practices Act (FRPA, AS 41.17) 2018). Only the economic feasibility, mostly just driven by operator cost and terrain, but not science-based sustainable forest management, limits the extent of timber taken. Consequently, not much old growth is left in those regions. However, compared to Canada, Alaska still features one of the largest uncut southern boreal forest blocks in North America; also free of roads.

There are new mechanisms proposed that might promote old-growth forest in Alaska such as the California carbon offset program (some details and examples shown here Morton 2019; see also Fresco 2006). However, those are concepts that are directly tight to virtually unconstrained industrial and contamination efforts in exchange, and their validity is not well proven yet, if even possible. Thus far, when it comes to carbon sequestration, there are a few—if ever—alternatives to old-growth forest maintenance, and when compared to felling and subsequent tree plantations, e.g. Luyssaert et al. (2008), Brandt et al. (2014), Law et al. (2018).

The Alaska situation was experienced and studied by the authors' first-hand for many years (see also publications cited above).

3.2.11 Inner Mongolia, China

Inner Mongolia is located in a steppe and desert area of inner Asia between Russia and China. Traditionally, nomads connected with Shamanism/Bon Buddhism dominated much of the area but those are now widely 'settled' and the state policy is not based much on spiritual values (Buckley 2021). As a consequence, soil erosion occurs now in many parts of the land. To fix the soil, one of the largest re-forestation programs in the world was initiated to increase forest cover (details in Zhang et al. 2022 for a review). Unfortunately, it features an area that never really had so many trees, nor the cloned species that get replanted. This not only results in failed reforestation programs but also a changing water table in an otherwise already dried up area. In this case, old-growth forests are not lost much, but steppe lands and deserts are turned into forests which then quickly die off and turn back into degraded land, on a large scale. Water irrigation projects take water from otherwise sparse areas and support failed projects in the desert. The initial steppe and desert, and its affiliated lifestyle and sustainability, is lost. Such schemes are not sustainable (Chen et al. 2018). In addition, many ancient old-growth-type trees can only be found in some fertile hill areas and valleys, namely willow and poplar. These details were seen first-hand by FH in several research trips.

3.2.12 Indonesia

Indonesia is known for its tropical lush environment. It has been covered by wild and widely untouched rainforests for millennia. However, in the last 50 years, Indonesia has reached a crisis point where forests are widely overcut, and now, palm oil plantations are replacing the old-growth forest in a dramatic fashion and in a record speed (see Cheyne et al. 2016 for impacts). Many of those tree plantations are supported by international forestry schemes, international money and international markets. They often feature 'certified' forest product schemes for the international market. This goes on the cost of the ancient rainforest and its species, with the Orangutan (*Pongo pygmaeus*) as an iconic species that gets tragically entangled and lost in this scheme. The reduction of tigers (*Panthera tigris*) and rhinoceros (*Rhinoceros sondaicus*), or hornbill species (Baral and Huettmann 2020), follows a similar scheme. In the meantime, Indonesia struggles with sustainbility while the human pressures are on the rise.

3.2.13 Vietnam

Vietnam is a nation with vast biodiversity, and it has had an extensive indigenous population for millennia. Vietnam features mid-elevation hills and extensive coastal zones and estuaries of global relevance, e.g. ecological services and fisheries. However, it is also affected by warfare, urbanization and other intense changes of the landscape in recent times, including the wide-spread use of Agent Orange. The loss of ancient forests is even pronounced in protected areas like national parks (Yen et al. 2005). FH has seen those details in several northern parts of the nation.

3.2.14 Nepal

Nepal is a tropical nation with mid-elevation hills, many low elevation areas and some but very famous high-altitude regions on the border to China. The initial forest cover was extensive, vast and ancient. The Sal (*Shorea robusta*) forest is of world fame, so is the old-growth forest of the Himalayas (see Jha et al. 2020; Awan et al. 2020). Forest cover was low in the 1970s due to unsustainable overcutting (e.g. Prajapati et al. 2020 for the shah regime). This forest area now increased due to afforestation supported by international aid (see Berger 2018, 2021 for 'Foto Monitoring' and applications and photos in Nepal). However, these new forests do not produce the original forest cover and diversity, or any old-growth structures. In the meantime, species like hornbills and woodpeckers are on the decline (Baral and Huettmann 2020).

FH has seen those examples first-hand in the old-growth forests of the Himalayas, as well as the plantations of the Sal forest at the Indian border (more details shown in Regmi and Huettmann 2020).

3.2.15 South Korea

Located on the Korean peninsula, South Korea has fully embraced economic growth and neoliberal policies. It's affected by war and ongoing conflict. The landscape is shaped accordingly, with forests mostly located on mountain tops, in protected areas and then otherwise intensively managed ones. Those recent legacy transitions, with a loss of old-growth forest wilderness, are described in Bae et al. (2012) and Tak et al. (2007), referred to as the 'South Korea Forest Dilemma'. It comes with many consequences (Hyun et al. 2020; Kim et al. 2021). Forests also play a wider spiritual role in South Korea, such as for grave sites. The loss of old-growth forests on the finite area of South Korea can be seen in the river systems, namely riparian forests which are needed for water buffer. However, these issues present a big and recognized issue for flood control, including the estuaries (Woo 2010). South Korea also has heavily invested in pine plantations for fast timber production; those are obviously done on the cost of the initial diverse temperate forest cover and its many species.

FH has seen those examples first-hand around Seoul, in the hills and the northern and southern parts of South Korea.

3.3 Confronting FAO Statistics Data on the World's Forests

The statistic of national forest cover is quite a political metric. It has received a lot of public attention and scrutiny. No wonder then those involved nations, NGOs and global institutions are on the look-out. The FAO STAT database is one of those information sources; we looked at this publically available data set closer and found little change in the established nations of the forest cover during the last 30 years. While national forest cover varies among nations, the annual fluctuations are relatively small in that data set. However, two details are notable: (1) old-growth forest is not well inventoried or tracked; (2) the overall national forest cover rarely increases but remains stable or slightly declines. It may safely be concluded that sustainable forest management keeps the status quo but does not inform, nor really and truly improve old-growth forest wilderness areas. It essentially ignores old-growth forest and such a reporting for the world's public. This matches the generic conclusion from previous sections in this assessment.

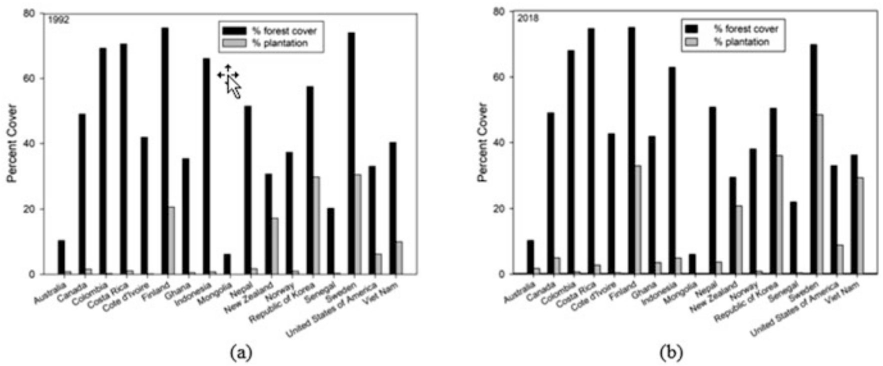

Fig. 3.2 Percent forest cover and percent forest in plantations for the years 1992 (**a**) and 2018 (**b**) for a selected set of nations in this meta-analysis; source: FAO STATS 2021

Table 3.1 Additional selected details regarding reforestation efforts and impacts on initial vegetation and ecology

Nation	Reforestation effort	Old-growth forest area lost	Comment
Scotland and North England	Sitka spruce	Virtually no old-growth forest left	Sitka spruce is heavily planted in wetlands. The latter is a widely retreating habitat type either way already, that now gets 'flooded' with invasive trees. While they blow over due to lack of a proper root system, they still fall 'into money' as they get harvested and sold that way for 'lower quality' timber
Iceland	Pine forest plantations	Iceland is rather barren and was never much forested in recent times; old vegetation consists of ancient moss (miniature) 'forests', subarctic tundra and volcano terrain, etc.	This is a classic example of modern neoliberal tree plantations taking over traditional vegetation types on a finite space. These new and heavily subsidized forests bring with them a changed species composition, e.g. birds and insects, as well as modified water tables
Caribbean Islands, e.g. Cuba, Puerto Rico, Jamaica	Pine forests, teak plantations, etc.	Many of those Caribbean islands have experienced a massive loss of old-growth forests, and various re-plantation efforts have been undertaken but almost none have brought back the initial virgin forest	Francis (1995) for Puerto Rica where most rainforest remaining is found in protected area and steep cliffs
Alaska Interior, USA	Planting of white spruce when natural regeneration is insufficient to meet reforestation objective	Extensive stands of old-growth white spruce remain because they are currently commercially unavailable due to the great distance from the built infrastructure and relatively low value of the resource	White spruce seeds are collected by local foresters and the seedlings are grown out of state and then shipped back to Alaska. The cost of this combined with planting often exceeds the value of the harvested tree. A shift to more natural regeneration occurred

(continued)

Table 3.1 (continued)

Nation	Reforestation effort	Old-growth forest area lost	Comment
			following a study that demonstrated that natural regeneration does occur but is often delayed for up to 10 years following a harvest (Morimoto et al. 2017)
European Union (EU)	Subsidized Xmas tree plantations, e.g. under power lines	Fragmentation of initial old-growth forest land	This scheme is meant to be a WIN-WIN situation for everybody: customer, public, powerline operator and plantation company. However, powerlines are environmentally very problematic, e.g. climate change, fragmentation and bird strike and electrocution. The actual Xmas tree plantations are far removed from a relevant local forest and are not in support of old-growth forests whatsoever
West Africa	Plantations of introduced species	Being lost due to: selection cut of desirable species, agricultural expansion and charcoal production	Plantations are more easily managed for production forestry and create products that can be more readily exported. Loss of biodiversity and soil fertility is major problem associated with this shift
China	Massive replantations with DNA cloned species, e.g. poplar nationwide, including in desert areas of Inner Mongolia (Chen et al. 2018), etc.	Ancient landscapes, including old-growth forests and their species, are widely lost in the last century, e.g. Elvin (2006), Harris (2014)	China is likely the world leader in tree plantations; (for an assessment see work by Zhang et al. 2022)

Table 3.2 Tools used for the so-called 'Sustainable Forest Management'

Name of tool	Example of its failure	Comment
Forest inventory	Boreal forest, tropical rainforest	Most of the boreal forest, or the tropical rainforest, are free of any plot-based long-term forest inventory in the field with a relevant research design, e.g. gridded, addressing taxonomy, scale and autocorrelation. While remote sensing is usually done and promoted as an alternative, this method is not on the ground and it widely fails on a consistent, compatible and coherent forest inventory needed for sustainable management, e.g. standing timber volume and reliable taxonomy. It further has a very difficult time monitoring and expressing forest structure and old-growth attributes
Growth-and-yield tables and models	Rainforests with easily over 500 species, long-term data requirements	This is the 'bread and butter' for modern forestry activities because growth-and-yield tables and their models set the stage and quantitative baseline for the profitability of the forest, the forest and land bids, as well as for banking and investment interests and their certainties
Thinning	Old-growth forest wilderness destruction and fragmentation	No old-growth forest can be thinned, nor can remote wilderness as it requires a road system
Salvage logging	Old-growth forest wilderness destruction and dead timber/ biomass removal	Fire is part of old-growth forest landscapes, and dead wood must not be removed
Economic assessments	EU lack of wilderness	The EU forests might make some money perhaps, but the natural resources remain subsidized overall while the initial old-growth forest is widely gone
Carbon sequestration	Fire	In the United States alone, over the past 10 years an average of 3.04 million ha burns annually releasing approximately 60.8 million mg of carbon into the atmosphere
Governance policy	Man-made climate change and CO_2 release widely unaddressed	Thus far, no global administrative governance consensus was found
Parsimonious reductionist science and modelling	Hypothesis testing, linear regression and AIC	These remain the predominant analysis methods for such topics

(continued)

Table 3.2 (continued)

Name of tool	Example of its failure	Comment
Publications	Status of the world's forest reports	Humans consume energy and resources on a finite planet; it can and should be done in a sustainable, transparent and modern/digital accessible fashion. However, those details are rarely acknowledged, discussed or promoted 'in the literature'.
Remote sensing	Old-growth forest mapping	From space, forest structure of old-growth forest cannot really be detected with satellite images
Subsidies	Old-growth forests, likely farming	Financial Handouts are rather problematic of natural resources are to be conserved
Neoliberal policies overall	Efficiency and optimization promotion while the actual wilderness area declines	See Jevons paradox (https://en.wikipedia.org/wiki/Jevons_paradox) and Daley and Farley (2010)

3.4 Synthesis of the Review

Nations show various degrees of forest cover and percent of the forest as plantation (Fig. 3.2). There is vast evidence that old-growth forests and their landscapes -wilderness- are disappearing. The concept of sustainable forestry has not halted this trend whatsoever, but it operates with tree plantations promoting thinning and similar road-intense efforts on the same and competing landmass, and this makes the situation for endemic old-growth forest wilderness much worse. While forests and tree plantations can sequester carbon, their contributions are 'tiny', e.g. when compared to ocean contributions and when considering events like forest fires while the core culprit—industrialization—is proceeding unabated (Tables 3.1 and 3.2).

3.5 Commonalities Across the World Regarding So-called Sustainable Forestry and Its Associated Loss of Wilderness and Old-Growth Forests

Forestry removes wood (Von Gadow 2001). Modern forestry employs latest technology to do so, e.g. maps created by geographic information systems (GIS) and remote sensing, computer models—now online—the combustion engine and helicopters. If done in a sustainable fashion, it requires expensive technical resources and computational methods and procedures to obtain an optimized and achieved balance between harvest and re-growth, e.g. Huettmann et al. (2005). The actual tree biomass removal is nowadays done by tractor—combustion engine—and similar tools. Thus, an infrastructure, including a road network, is needed. Roads are one of the best indicators of those forest practices unless tree harvests are employed using helicopters. The latter still need an airport and a connecting road system to operate. In many forestry operations, roads are an inherent part of the business model (see Tongass Forest, Schoen 2021). Roads stand in a direct conflict to remoteness and wilderness (e.g. Bocharnikov and Huettmann 2019). Further, forestry and associated development is now widely just seen as an investment project by banks and companies (Huettmann 2020 for an example); usually on an international scale. Most large forestry operations include banks and their schemes of interest rates. But as forests can burn, it usually also involves insurance. The latter use and receive a large number of funds from other sources. Thinning is widely done and promoted as a sustainable method but the requirement of roads and access gets usually overlooked. Salvage logging is another operation that comes with burned forests but which remains unsustainable and poorly managed also. Many of those schemes are not very lucrative, but can easily become so with political support and subsidies, which then trigger such a style of extraction-based forestry. This is well documented for areas like Tongass, Alberta in Canada, Eastern Canada and also with international aid money for climate change issues.

For instance, economic data from Southeast Alaska report that the timber industry accounts for less than 1% of the region's labour force while seafood and tourism combined account for about 25%. According to 'Taxpayers for Common Sense', the Tongass National Forest lost an average of $30 million annually on its timber management program. A case can easily be made that those forests and their science-based 'sustainable' management are not well managed and result into a sink on many accounts: financially, socially, environmentally and climate-wise. Such a forestry scheme then must be judged as a 'culture gone wrong'.

3.6 Old-Growth Forests Cannot be Harvested, Re-built, or Managed Sustainably by the Western Institutions, Thus Far

While sustainable forestry is promoted worldwide, and on the rise with the tree plantation models (Victor and Ausubel 2000; Wernick et al. 2008), it is widely forgotten and ignored that old-growth forest does not suit this model at all. Those models of forestry are opposed to each other arguably, the European science-based forest management example, which dominates much of the world, and is now promoted by the U.S. and United Nations (UN) globally, is a good example of it: initially covered by old-growth forest, by now, the EU is virtually free of any wilderness tracts; it is also clear for the main parts of the U.S. other than Alaska (Huettmann 2011, 2014). The biggest wilderness areas are now found in the remote ocean. This fact applies specifically for areas that are managed under a sustainable forestry scheme for several centuries (see Elvin 2006 for China). Virtually none of those have ever re-created old-growth forest wilderness, nor is that on their plan and outlook, as part of their reductionist and rigid implementation (Wohlleben 2016; Simard 2021; see Bhagwat and Rutte 2006 for a spiritual culture of sacred groves. Science-based sustainable forest management does not support old-growth forest and wilderness; it is not designed that way, it cannot understand and comprehend it and it stands in direct competition with its eliminating old-growth forest. That is even more so the case when forestry gets now heavily industrialized, commercialized, legalized, subsidized and institutionalized, globally.

3.7 Woodpeckers as a Central Indicator Species for Old-Growth Forests and Tree Plantations

Most woodpeckers need trees to nest; ideally big trees. If suitable trees are gone, then there will be no wood peckers. Woodpeckers are part of a wider ecological community such as specific fungi and insects living in dead standing trees. Arguably, big wood peckers need big trees—ideally dead ones (Baral and Huettmann 2020), and those will be affected first when landscapes with old-growth forests are disappearing (a typical example can be found in the U.S. and Cuba with the Ivory-billed Woodpecker, e.g. Lammertink and Estrada 1995). However, virtually any woodpecker community and ecosystems are affected when modern science-based forest management enters a landscape. Most woodpeckers are primary cavity nesters, and thus, they need dead standing wood, ideally of large diameter breast height (DBH) and that rots away slowly over decades. But the ecosystem of dead and coarse woody debris (CWD) in a forest and in a landscape is something that is widely discouraged, erased (Von Gadow 2001), in modern forestry. That is because 'quality wood' is to be free of insects and fungi and the prime production aim.

Several other indicator species can be named for old-growth forest types, e.g. for their areas of retreat (for bears see Howlett et al. 2009; Gailus 2010; Nielsen et al. 2008, for parrots see Resendiz-Infante and Huettmann 2015). But few species have such a general indicator value for trees across the world than woodpeckers have. Arguably, the global success model of modern sustainable forestry stands in direct conflict with woodpeckers and has widely reduced, if not eliminated, the worldwide already. Likely we currently just see the last remnants of the woodpecker community that was very abundant for millennia.

3.8 A Climate Change Perspective Added: Old-Growth Forest Loss Makes It Worse

Forestry has been seen early on as a mitigation project for climate change, carbon sequestration (Kumar et al. 2019a, b). This might make sense initially, but still excludes most of the oceanic perspectives (app 2/3 s are covered by oceans, whereas forests just cover 1/3 of the landmass, which in itself just makes 1/3 of the Earth). Plankton, fish and whales play a much larger role in the carbon cycle than most trees (e.g. Pershing et al. 2010) and within that, many forest areas are not always managed for carbon sequestration. Man-made climate change, as mainly driven by man-made CO_2 and methane release, and thus an industrial waste problem, is not well tackled in industrial forestry, which has a carbon footprint, besides other impacts (Singh et al. 2020) (for instance many forest plantations require herbicide and insecticide treatments). Some of those 'modern forest management' schemes, e.g. ones with a big administration or using helicopters, can release more carbon than they claim to save (a typical feature in virtually all industrial and western activities). The true and relevant aspect of climate change is not addressed when knowing that untouched old-growth forests are among the best land-based hedges against species loss and climate change impacts (temperate ancient rainforests are too wet to burn and thus lack fire). In sustainable forestry, as well as the UN SDGs, we lack a wider recognition of such concepts for old-growth wilderness.

To show those details for the boreal forest, as the largest contiguous forest in the world: Russia's boreal forest gets increasingly fragmented by roads (Bocharnikov and Huettmann 2019). The Scandinavian and Canadian boreal forest has many species reduced or lost (Collard et al. 2019). Alaska's boreal forest has experienced some of the greatest magnitudes of climate-driven change of any forest region. An adaptive management framework is required to deal with the changing face of forest management. Historically in this region, reforestation has relied heavily on natural regeneration, which has been more successful than traditional planting efforts. This is likely due to the nature of most harvests being small and targeted mature white spruce near roads. Additionally, wildfires were small to very large and occurred broadly. However, given an increased demand for timber and a changing climate, these conditions are changing. Now post-harvest regeneration is less successful as seen on dry sites where failure already occurs due in part to changing size of clear-cuts and the competition with species such as *Calamagrostis canadensis* and *Epilobium angustifolium* (Gärtner et al. 2011). However, the boreal forest in some landscape positions can be highly resilient to additional warming or invading tundra.

3.9 Some Simple Truisms and Take-Home Messages

So-called sustainable forestry is not sustainable on a finite landmass and planet. That is easy to see on many metrics, and true on a global level. It follows concepts shown by Klein and Magomedova (2003) and Czech (2002) (see Daley and Farley 2010 for an economic foundation).

Forestry institutions and their education systems, science, syllabi, budgets, faculty positions and graduates widely fail on those old-growth forest aspects and widely present a hindrance on good progress for old-growth forest landscapes (as expressed by Wohlleben 2016; Simard 2021 and experienced by many people worldwide including the co-authors). At minimum, it follows 'indifference', (Bandura 2007) and is not what science and management for the wider public good can do and provide.

Old-growth forest wilderness have one of the highest carbon sequestrations but are clearly not re-growing in just 100 years and in forests with such rotation period management leaving forest structure and how to manage and maintain it—unaddressed.

Forestry does not happen in a vacuum, it requires effective and well-functioning policy, legal institutions and instruments, governance agencies and a funding mechanism, e.g. a relevant tax system with sustainable industrial money to achieve (Kumar et al. 2019b).

Economic growth, globalization and neoliberal policies fail wilderness and the old-growth forest landscapes globally, but still promote a neoliberal type forestry, so-called sustainable (but which is impossible to achieve).

Unless these modern cultural problems of old-growth forest loss and management get recognized quickly, and then changed, old-growth forest areas and wilderness landscapes will decline further despite a modern 'sustainable forestry' and SDGs but with drastic consequences like extinction, warfare, poverty, human migration and generic conflict. Many of those details can already be seen today.

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4 Gangetic Plains of India: High on the Water and Air Pollution Map

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Abstract

As per global studies on atmospheric air quality at the Center for Ecology and Hydrology, UK and NASA, USA, the Indo-Gangetic Plain has emerged as a global ammonia (NH3) hotspot, due to which Himalayan foothills are experiencing "Alkaline air". Apart from existing threats of rapid land use change and overharvesting of forest products, preliminary investigations have reported forest dieback, invasion by invasive species including pests and pathogens, and low regeneration of forest trees in this region. Local communities in this largely agricultural landscape traditionally depend on these forests for their livelihood, including for firewood and nontimber forest products. Unless these impacts are studied in finer detail, with baselines developed and mapped, the health of the forest ecosystem will not receive conservation priority. Therefore, under the aegis of the South Asia Nitrogen Hub (SANH), this chapter attempts to undertake a preliminary study of the present status of pollution in the air, and for surface and groundwater and soil in the Indo-Gangetic plain, focusing on four states in India viz. Uttarakhand, Uttar Pradesh, Bihar, and West Bengal through which the Ganges flows. We also look specifically at lichens, which are known indicators of pollution. Our study reveals that while the region has shown enhanced levels of pollution of soil and water, the forest cover of the four states remains largely the same over time, though there has been a decline in both the NDVI (Normalized

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Difference Vegetation Index) and the EVI (Enhanced Vegetation Index) which are indicators of the greenness of the ecosystem.

Keywords

Indo-Gangetic plain · Pollution · SANH · Forests

4.1 An Introduction to Gangetic Plain of India: The Study Area

The Indo-Gangetic Plain (IGP) is an extensive fluvial system that emerged as a consequence of collision between the Indian and Chinese plates during Middle Miocene (Parkash and Kumar 1991). It developed alluvium from its large river system including the Indus, Yamuna, Ganga, Ramganga, Ghagra, Rapti, Gandak, Bhagirathi, Silai, Damodar, Ajay, and Kosi rivers. A variety of soils such as Entisols, Inceptisols, Alfisols, Mollisols, and Aridisols are all found in the IGP owing to regional differences in precipitation (Pal et al. 2009).

In the past, the IGP was very fertile as most of its area had been naturally forested, but continuous deforestation activities by the human population resulted in localized aridity and desert conditions (Randhawa 1945). During the nineteenth century, a canal system was introduced to mitigate problems associated with aridity and also to stabilize crop production. Consequently, this also led to an increase in cultivated area but absence of provision of drainage during dry climatic conditions resulted in soil salinization and alkalization (Abrol 1982; Pal et al. 2009). However, introduction of high input agricultural technologies over the last three-to-four decades has been very much successful in increasing crop production. Thus, the IGP has emerged as the major food production region of South Asia having rice and wheat as main crops as well as pulses, oilseeds, cash crops, and horticultural crops.

Use of modern technologies including the spread of high yielding varieties; expansion of irrigated areas; increased fertilizer use; introduction of plant protection chemicals; and also inception of government subsidies resulted in soil degradation, loss of soil carbon and fertility, nutrient imbalance, depletion of natural resources, contamination of sub-surface water by nitrogen, phosphorus, and heavy metals, drainage congestion, and further consequences (Velayutham et al. 2000; Bhandari et al. 2002; Gupta 2003). In addition, the use of heavy agricultural machinery has resulted in hard pan formation (Bhattacharyya et al. 2005) that directly causes an increase in soil bulk density and a decrease in saturated hydraulic conductivity. Such changes in soil physical properties either significantly decrease or stagnate crop production especially wheat in the upper part of IGP (Ray et al. 2014). Moreover, traditional on farm burning of huge quantities of crop residue to prepare fields for succeeding crops (the rice—wheat system) causes a loss of soil organic matter, loss of both micro and macro nutrients, reduction of microbial biomass and activities, and further facilitates soil erosion (Kumar et al. 2019).

The South Asia Nitrogen Hub (SANH), supported by Global Challenge Research Fund, UK, focuses on increased levels of pollution in the IGP spanning through the

Fig. 4.1 Map showing the study region in the study

countries Afghanistan, Pakistan, India, Nepal, and Bangladesh. This study is an attempt to develop a preliminary present status report of pollution in air, surface, and ground water and soil in the IGP focusing on four states *viz*. Uttarakhand, Uttar Pradesh, Bihar, and West Bengal through which the Ganges flows. Figure 4.1 shows the region of study (Gangetic Plains (GP)).

Our interest has been to look at the IGP in India with respect to its present status of the air, soil, and water pollution. The livelihoods of more than 600 million people, covering three major countries (India, Bangladesh, and Nepal) of South Asia, are directly linked to the IGP. Being a fertile basin with immense water availability, it has become a hub of biological and cultural diversity, a source of agriculture-based income generation and historically rich (Sharma et al. 2010; Amarasinghe et al. 2016; Surinaidu et al. 2020). Consequently, more than 65% of the basin has been ORIS agricultural land. Availability of natural resources also leads to establishment of various industrial units in the basin that includes but is not limited to textiles, wood and jute mills, sugar mills, distilleries, pulp and paper mills, dairies, pesticide plants, and tanneries (Dwivedi et al. 2018; Ghirardelli et al. 2021). Thus, overexploitation of water resources by both agricultural and industrial activities puts the IGP under extreme pressure while there is continuous addition of pollutants from industrial effluents, agricultural runoff, and religious activities. The heavily industrialized area from Kanpur to Allahabad (middle Ganga plain) appears to be the most polluted stretch of the IGP (World Bank 2012; Misra 2011; MacDonald et al. 2015). The level of heavy metals in sediments of the Ganga is continuously rising (Pandey et al. 2009; Pandey and Singh 2017), on the other hand researchers are identifying different kinds of organic pollutants in the surface water and or sediment samples from the Ganga basin. A total of 10 groups (reported as cumulative concentrations) and 261 individual organic compounds have been reported by 28 individual publications, covering big urban agglomerations including Delhi, Kanpur, Allahabad, Varanasi, Patna, and Kolkata (Ghirardelli et al. 2021). Most recently, a study has found several strains of bacteria in water samples from the Ganga that are resistant to antibiotics. Residual antibiotic compounds containing effluents from drug manufacturing units, hospitals, and the poultry industry are believed to be the main cause of appearance of these resistant strains. Thus, use of such water may give rise to bacterial infection that could become untreatable (Reddy and Dubey 2019; Ali et al. 2021). The paragraphs that follow provide an account of ground and surface water pollution, nitrogen dioxide (NO_2), and PM2.5 keeping in view the key focus on nitrogen pollution by the SANH project, and land use cover change that is now required to assess the forest health. The study here relies on secondary literature for water pollution and extract concentrations of the aforementioned pollutants, while outlining the change in land use and land cover through satellite data.

4.1.1 Ground and Surface Water

During the summer season and in dry areas of the IGP, borewell water is the most reliable source of irrigation. A study by Mishra et al. (2018) reveals that the IGP has more than 90% of its area irrigated with ground water resources. Government initiatives for direct procurement of rice and wheat from arid regions, plus subsidized energy costs for agricultural pumping systems, have encouraged the increasing use of ground water in India. India withdraws about 230 billion m^3 of ground water to irrigate 45 million ha of gross cropped area (Shah et al. 2012). Consequently, a majority of districts of India have experienced a decline in annual ground water levels over the past 21 years (1996–2016). A few districts having a substantial decrease in water level are found in Punjab where the depletion rate is reported as high as 91 cm/year (Singh et al. 2011; Mishra et al. 2018). According to the recent ground water resource assessment report (CGWB 2018, 2019), there is a considerable spatial and temporal variability in ground water extraction in the IGP region. More than 100% ground water extraction has been reported in areas including Punjab, but also Rajasthan, Haryana, and Delhi, indicating over exploitation of resources. In other Indian states of the IGP, the current stage of ground water extraction is observed to be in the range 45–70% and the country average is 63.3% (Fig. 4.2). We also provide figures for comparison with other states of India, and neighboring countries Bangladesh and Nepal in the plain.

Water quality is described in terms of concentration of some specified contaminants present in the water and certain physical characteristics of the water. Salinity, chloride, nitrate, fluoride, arsenic, and iron are the most commonly observed geogenic contaminants in the ground water. According to the current report published by Central Ground Water Board of India, a high level of salinity (>3000 microS/cm), chloride (>1000 mg/L), fluoride (>1.5 mg/L), iron (>1.0 mg/L), arsenic (>0.05 mg/L), and nitrate (>45 mg/L) has been found in 69, 33, 77, 103, 18, and 117 districts across eight Indian States in the IGP, respectively (Table 4.1).

Among the different parts of IGP, West Bengal in India has the largest population at risk of exposure to arsenic contamination. In West Bengal, an estimated six million people have been exposed to relatively high arsenic concentrations, ranging from 0.05 to 3.2 mg/L (Mohan and Pittman 2007; Adeloju et al. 2021).

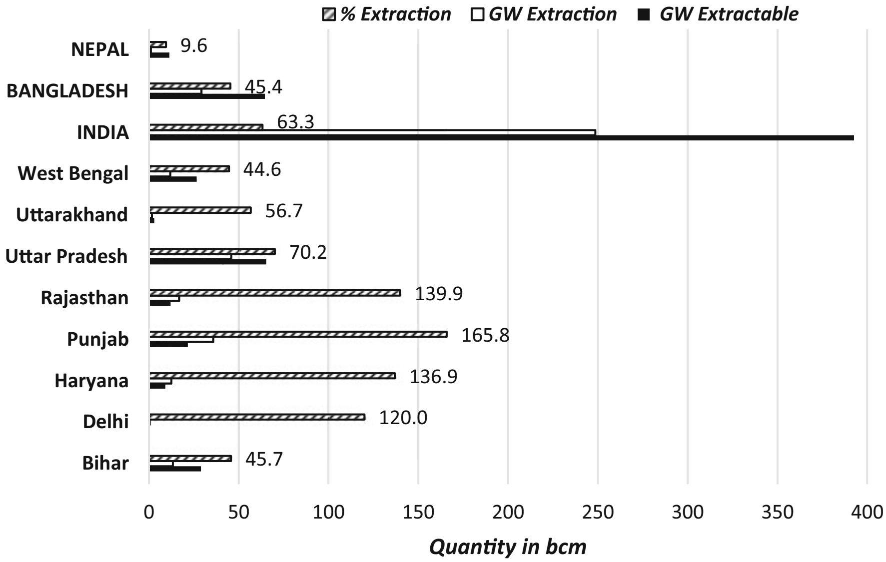

Fig. 4.2 Ground water resources and its extraction status across the IGP (compiled from CGWB 2019; Surinaidu et al. 2020)

Table 4.1 Indian states and districts across the IGP, affected by contaminants in ground water (compiled from CGWB 2018)

States of India	Values for districts that have high level of contaminants					
	Salinity >3000 ms/cm	Chloride >1000 mg/L	Fluoride >1.5 mg/L	Iron >1 mg/L	Arsenic >0.05 mg/L	Nitrate >45 mg/L
Bihar	02	–	05	21	02	21
Uttar Pradesh	10	02	18	15	05	31
Uttarakhand	–	–	01	–	–	3
West Bengal	07	01	04	15	06	–

In India, the CPCB (Central Pollution Control Board) together with the SPCB (State Pollution Control Board) are regularly (monthly/yearly) monitoring (since 2009) a few selected water quality parameters (termed as "Core Parameters") of the Ganga river to assess the existing pollution load and suggest possible measures to improve water quality. The core parameters include temperature, pH, EC (electrical conductivity), DO (dissolved oxygen), BOD (biological oxygen demand), nitrate, FC (fecal coliform), TC (total coliform), and sometimes FS (fecal streptococci). During 2019, a total of 96 monitoring stations covering five states (Uttarakhand, Uttar Pradesh, Jharkhand, Bihar, and West Bengal) were monitored. According to the published data of the year 2019, a gradual deterioration has been found in water quality starting from Uttarakhand through to West Bengal as the Ganga travels from hilly areas to flat basins and finally ends at the Bay of Bengal (Table 4.2). However,

Table 4.2 Current water quality status of Ganga water in different states of India (compiled from CPCB 2019)

Core water parameters	States of India through which river Ganges flows				
	Uttarakhand	Uttar Pradesh	Bihar	Jharkhand	West Bengal
Temperature (°C)	16–28	14–33	13–37	17–44	17–37
pH	7.1–8.4	2.2–8.8	6.6–9.9	7.6–8.6	6.8–9.0
EC (μmho/cm)	97–400	62–789	16–629	304–322	155–18,090
DO (mg/L)	8.6–11.8	4.6–12.2	5.6–10.2	7.8–8.6	3.5–11.5
BOD (mg/L)	1.0–2.0	0.6–5.8	1.1–2.9	2.2–2.8	0.5–8.0
Nitrate (mg/L)	NA	0.12–1.83	0.01–1.83	NA	0.05–6.32
FC (MPN/100 mL)	2–220	$2 - 3.5 \times 10^4$	$170 - 3.5 \times 10^4$	NA	$400 - 1.3 \times 10^6$
TC (MPN/100 mL)	2–401	$170 - 6.3 \times 10^4$	$1400 - 1.6 \times 10^5$	NA	$1100 - 3 \times 10^6$

NA not available

intrastate variation of a few parameters is very wide in some states, e.g., the pH value in Uttar Pradesh has been recorded from 2.2 (highly acidic) to a maximum of 8.8 (highly alkaline).

4.2 Atmospheric Pollutants: Nitrogen Dioxide (NO_2) and Particulate Matter PM2.5

Our study to assess the levels of atmospheric pollution in the IGP has been focused on NO_2 and PM2.5, integrating it with the research focus of the South Asia Nitrogen Hub (SANH). The data collected for the NO_2 and PM2.5 were through GIOVANNI (giovanni.gsfc.nasa,gov) for four time periods per year viz., Summer (March, April, and May), Monsoon (June, July, and August), Autumn (September, October, and November), and Winter (December, January, and February) and for the four states, namely Uttarakhand, Uttar Pradesh, Bihar, and West Bengal. Time averaged maps of monthly data were also acquired from the Ozone Monitoring Instrument (OMI) sensor aboard the Aura satellite. Aura is a sun synchronous satellite with a global coverage and records data at 13:30 PM local time. At nadir, its resolution is 13×26 km^2, achieved once in 16 days, but with wider swathes sampled, gives 60 each of 2600 km. The spectrum used is 405–465 nm for NO_2, employing Differential Optical Absorption Spectroscopy (DOAS). The data retrieved are the total column density (Bechle et al. 2013).

PM2.5 was measured by The Modern-Era Retrospective analysis of the Research and Applications version 2 (MERRA-2). It employs the Goddard Earth Observing System Model, Version 5 (GEOS-5), along with the Atmospheric Data Assimilation System (ADAS). It provides global data using Aerosol Optical Density (AOD). Its spatial resolution is $0.5^\circ \times 0.625^\circ$ and temporal resolution is 1 h.

Seasonal variations of these two pollutants in Summer, Monsoon, Autumn, and Winter in the GP, and their respective trends in the four states, Uttarakhand, Uttar Pradesh, Bihar, and West Bengal are shown in Figs. 4.3a–4.4h.

As shown in Fig. 4.4a and b, significant seasonality has been found for both the pollutants ($p < 0.05$; Table 4.3), but no long-term trends are observed in terms of NO_2 and PM2.5 concentration (Table 4.4), for the targeted states and during the time frame 2012–2020 (Tables 4.5 and 4.6).

Since no trend or seasonality was observed in this 9-year's period, a shorter duration of 3 years was considered and analyzed for seasonality and trends. This time period was from 2018 to 2020. The graphs and tables (Fig. 4.5 and Tables 4.7, 4.8, 4.9, and 4.10) so obtained are attached below.

Our observations with respect to NO_2 and PM2.5 are as follows.

1. A high seasonality is demonstrated by the Friedman test for all states of the GP (Bihar, Uttar Pradesh, Uttarakhand, West Bengal) for both the pollutants NO_2 and PM2.5 as well as both the time scales considered.
2. Using a Mann Kendall test, trends appear stationary (nonsignificant) for NO_2 as well as PM2.5 through the satellite data collected for the years 2012–2020.

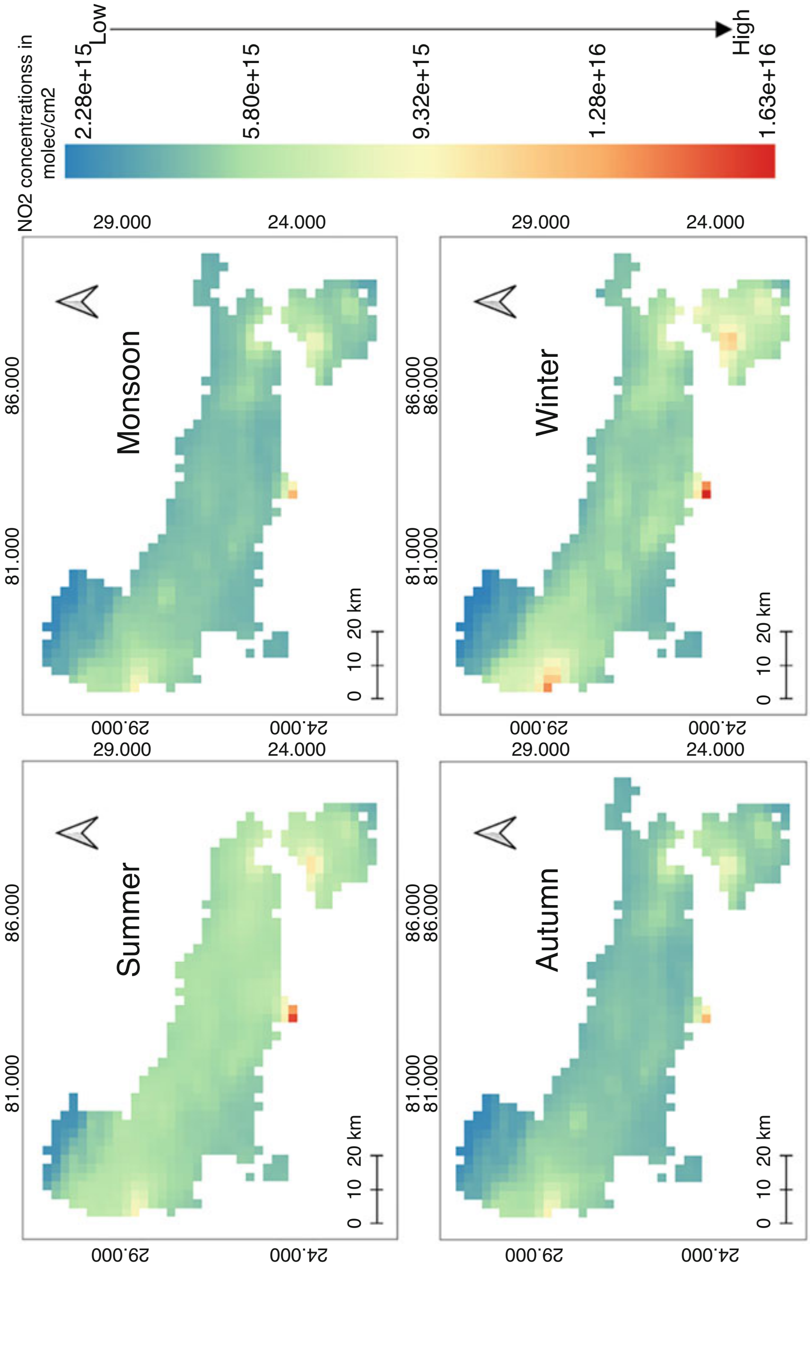

Fig. 4.3 (**a**) Seasonal variation in NO2 concentration across the Gangetic plains (2012–2020). (**b**) Seasonal variations in PM2.5 concentrations across Gangetic plains (2012–2020)

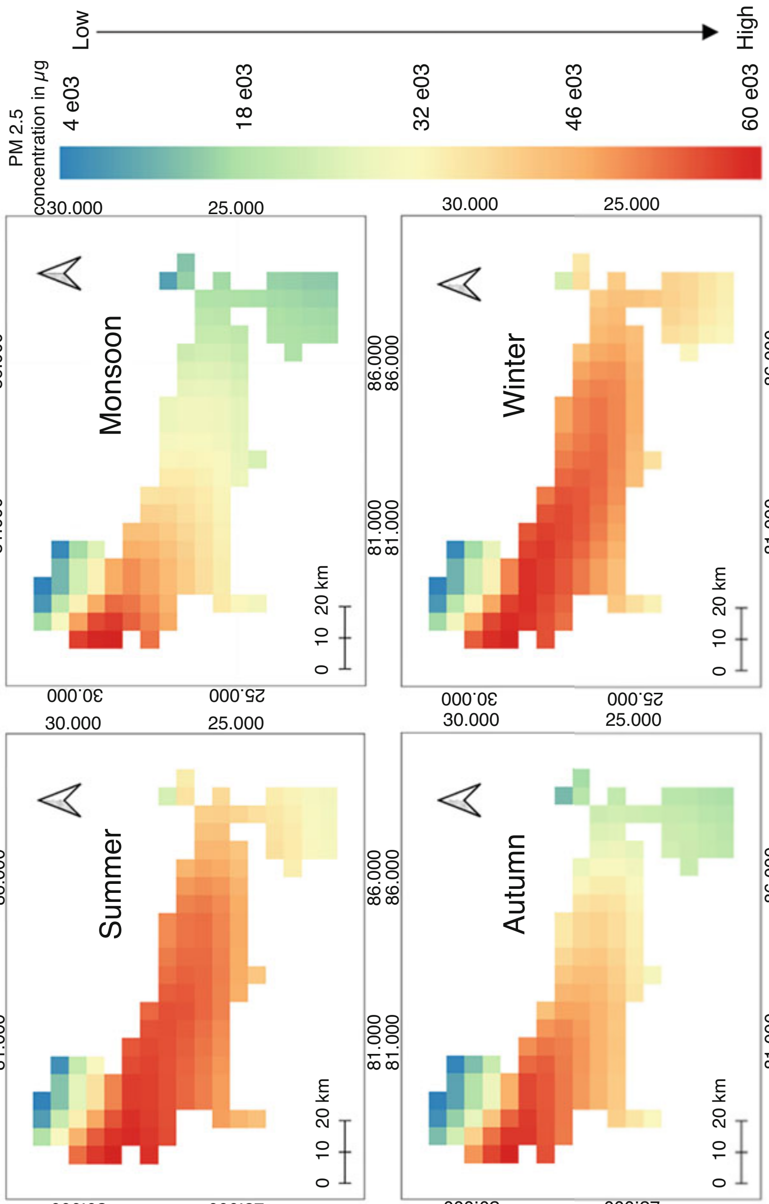

Fig. 4.3 (continued)

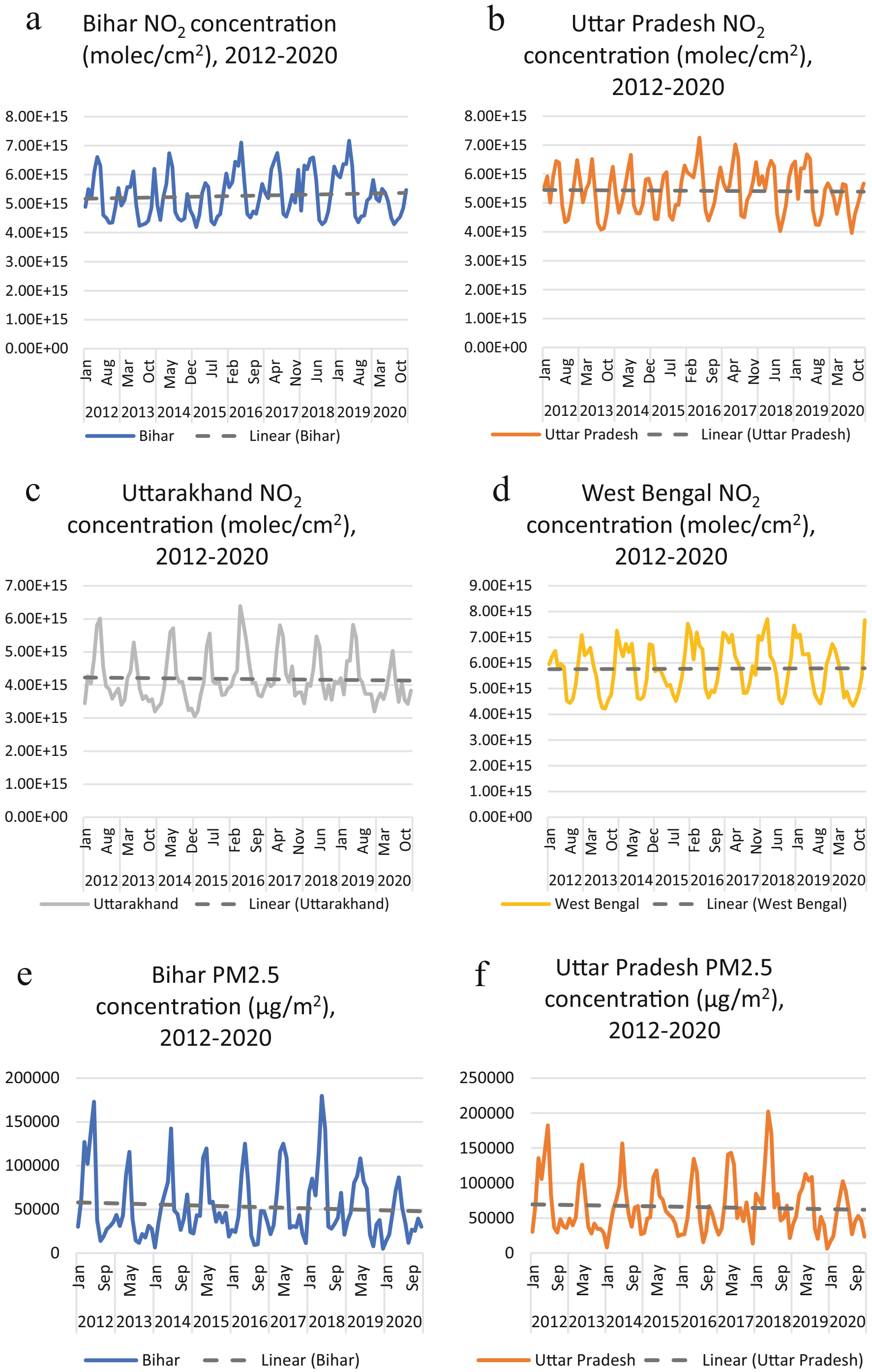

Fig. 4.4 (**a–d**) Trend analysis for NO_2 concentrations (molecules/cm^2) (2012–2020). (**a**) Bihar; (**b**) Uttar Pradesh; (**c**) Uttarakhand; (**d**) West Bengal. (**e–h**) Trend analysis for PM2.5 concentrations (µg/m^2) (2012–2020). (**e**) Bihar; (**f**) Uttar Pradesh; (**g**) Uttarakhand; (**h**) West Bengal

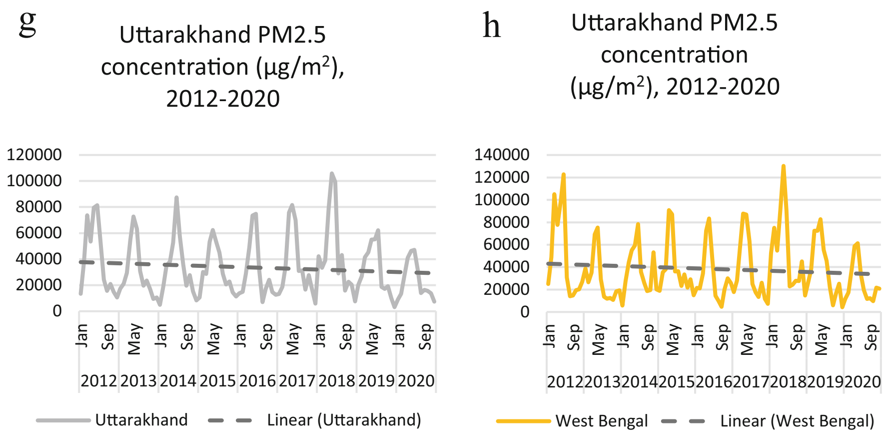

Fig. 4.4 (continued)

3. However, there is a significant downward trend for PM2.5 for the more recent past (2018–2020) in the states of Uttarakhand and West Bengal as compared to the years 2012–2020. NO_2 as well shows a statistically significant downward trend in the states of Bihar and West Bengal ($p < 0.05$). Lockdowns due to COVID-19 pandemic may or may not have had a contribution to this observation.
4. The maps show differences in pollution gradients among different seasons.
   (a) NO_2.
   - Summer and winter months have the highest pollution concentration in the atmospheric column for the Gangetic Plains.
   - Monsoon and autumn show lower concentrations.
   - Except for a couple locations, pollution seems homogeneous.

   (b) PM2.5.
   - Summer and winter again show the highest pollution concentration levels in the atmospheric column for the Gangetic plains.
   - Monsoon and autumn show lower concentrations.
   - Clear distinction in high and low pollution areas is visible.

The high pollution in the months of summer and winter could be attributable to harvest of crops, which happen March–April in summer and October–November in winter for both the pollutants. In winters, the NO_2 concentration rises due to burning of various fuels for warmth (Gupta et al. 2003).

Table 4.3 Seasonality analysis for NO2 concentration using Friedman test 2012–2020

Location	Friedman chi-squared	Confidence level	*P*-value
Bihar	89.461	95%	6.277e-14
Uttar Pradesh	95.846	95%	3.61e-15
Uttarakhand	86.429	95%	2.417e-13
West Bengal	93.962	95%	8.407e-15

Table 4.4 Trend analysis for NO2 using Mann Kendall test 2012–2020

Location	MK tau	Confidence level	*P*-value
Bihar	0.0621	95%	0.34319
Uttar Pradesh	−0.00988	95%	0.8818
Uttarakhand	−0.0101	95%	0.8797
West Bengal	0.000866	95%	0.99153

Table 4.5 Trend analysis for PM2.5 concentration using Mann Kendall test 2012–2020

Location	MK tau	Confidence level	*P*-value
Bihar	−0.0284	95%	0.66521
Uttar Pradesh	−0.0232	95%	0.72402
Uttarakhand	−0.0762	95%	0.24383
West Bengal	−0.0703	95%	0.28228

Table 4.6 Seasonality analysis for PM2.5 concentration using Friedman test 2012–2020

Location	Friedman chi-squared	Confidence level	*P*-value
Bihar	89.461	95%	6.277e-14
Uttar Pradesh	95.846	95%	3.61e-15
Uttarakhand	86.429	95%	2.417e-13
West Bengal	93.962	95%	8.407e-15

4.3 Status of Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI), and Land Use Land Cover Change Assessment in the IGP

Our study for two decades (2000–2020) reveals a fluctuating NDVI and EVI using the MODIS product MOD 13Q1 006 at 250 m resolution (Fig. 4.6a and b); there is a fluctuating trend but a downward trend over the last 5 years. It was pertinent to study at least a decade of land cover change in our region of interest (Fig. 4.6a and b).

To develop a long-term perspective for sustainable planning and for assessing the contribution of land cover change to the region, our study assessed land cover change using MODIS land cover product for the year of 2001 and 2019. We used a global land cover data product (MCD12Q1, Version 6) derived from Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) at a 500 meter spatial resolution. The MCD12Q1 product is created by using supervised classification of MODIS reflectance data for the year 2001–2019 on a yearly interval.

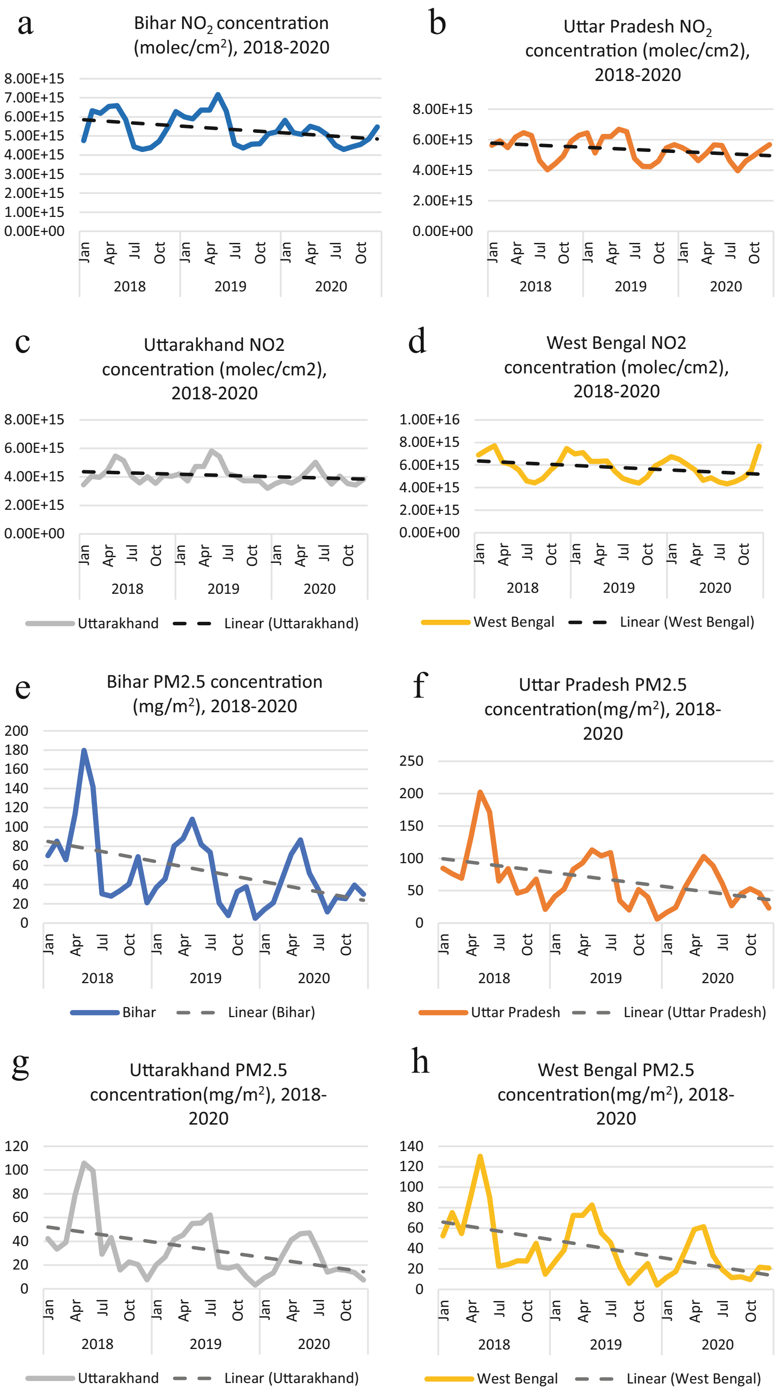

Fig. 4.5 (**a**–**d**) Trend analysis for NO2 concentrations (2018–2020). (**a**) Bihar; (**b**) Uttar Pradesh; (**c**) Uttarakhand; (**d**) West Bengal. (**e**–**h**) Trend analysis for PM2.5 concentrations (2018–2020). (**e**) Bihar; (**f**) Uttar Pradesh; (**g**) Uttarakhand; (**h**) West Bengal

Table 4.7 Trend analysis for NO2 using Mann Kendall test 2018–2020

Location	MK tau	Confidence level	*P*-value
Bihar	−0.231	95%	0.049768
Uttar Pradesh	−0.186	95%	0.11407
Uttarakhand	−0.17	95%	0.14875
West Bengal	−0.246	95%	0.035922

Table 4.8 Seasonality analysis for NO2 using Friedman test 2018–2020

Location	Friedman chi-squared	Confidence level	*P*-value
Bihar	32.304	95%	0.001242
Uttar Pradesh	32.634	95%	0.001104
Uttarakhand	26.699	95%	0.008537
West Bengal	32.587	95%	0.001122

Table 4.9 Trend analysis for PM2.5 using Mann Kendall test 2018–2020

Location	MK tau	Confidence level	*P*-value
Bihar	−0.273	95%	0.01985
Uttar Pradesh	−0.283	95%	0.015913
Uttarakhand	−0.311	95%	0.0079056
West Bengal	−0.371	95%	0.0015053

Table 4.10 Seasonality analysis for PM2.5 using Friedman test 2018–2020

Location	Friedman chi-squared	Confidence level	*P*-value
Bihar	30.462	95%	0.002378
Uttar Pradesh	29.143	95%	0.003752
Uttarakhand	30.198	95%	0.002607
West Bengal	30.742	95%	0.002156

The MODIS land cover product is derived from six different classifications schemes and divided into 17 different land cover classes. The supervised classification then undergoes additional postprocessing that incorporates prior knowledge and ancillary information to further refine specific land cover classes. The output MCD12Q1 data are provided as tiles that are approximately $10° \times 10°$ at the Equator using a Sinusoidal grid in HDF4 file format. MCD12C1 data are provided as a global mosaic in a geographic latitude/longitude projection and also in HDF4 file format (3600 rows $\times$ 7200 columns).

Land cover change has been assessed for the year 2009 and 2019 for the IGP using the MODIS land cover product (MCD12Q1) with spatial resolution of 500 m. The MODIS land cover product was downloaded from https://search.earthdata.nasa.gov/search in HDF format. Data were exported into .img format using ERDAS 14.5 software. Further, data were re-projected from sinusoidal to the UTM projection system to calculate the area under different land cover classes. As mentioned in the preceding paragraph, these 17 classes were further reclassified into five major categories including Crop land, Forest cover, Built-up area, Barren land, and

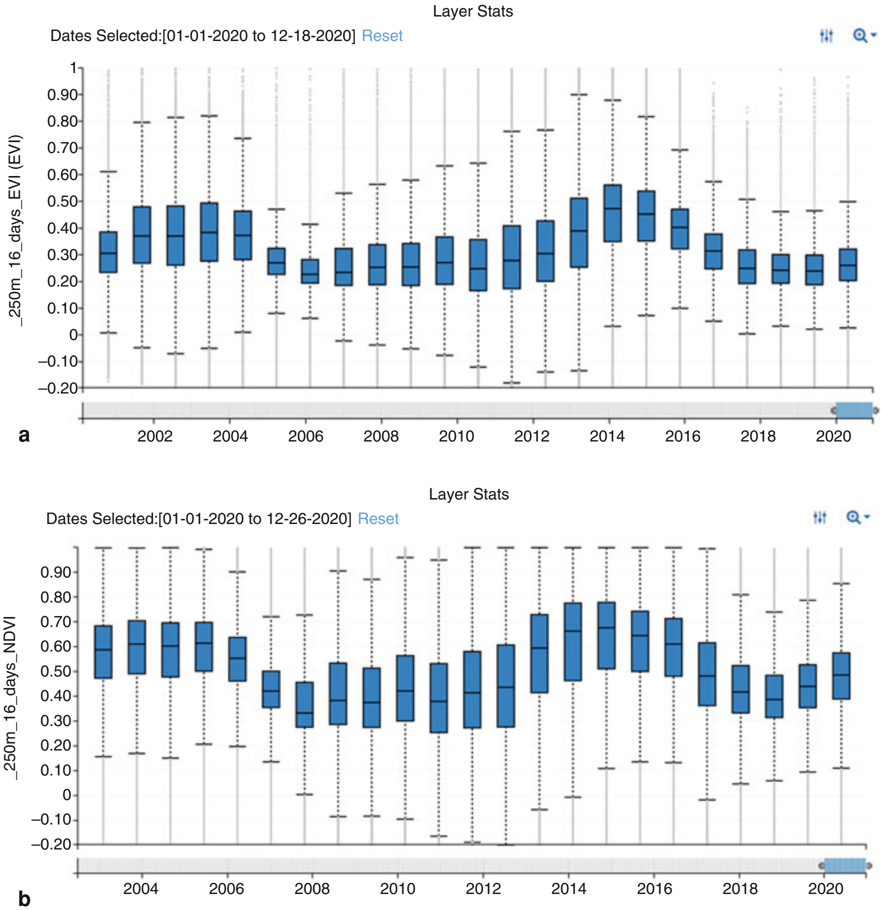

Fig. 4.6 (**a**) Trends in EVI in the IGP (2004–2018). (**b**) Trends in NDVI in the IGP (2004–2018)

Water for the change assessment. Land cover change has been assessed for each state separately and IGP as a whole.

The study examined state-wise land cover changes of the IGP region to identify the state which is more prone to land cover change during the last decade. Crop land decreased significantly (3.5%) in Uttarakhand though slight decreases were observed in other states excluding Bihar where crop land also increased slightly. Forest cover in Uttarakhand increased in last 10 years to 3.5% though almost no change in forest cover was detected in Uttar Pradesh. On the other hand, the built-up area in all the GP states increased to some extent, where barren land had been reduced in all states (Fig. 4.7a–c).

Results show that during the last decade (2009–2019), crop cover has been reduced significantly in the region, by around 2203 km^2 (0.45%), with also a significant reduction observed for barren land. However, forest cover increased in

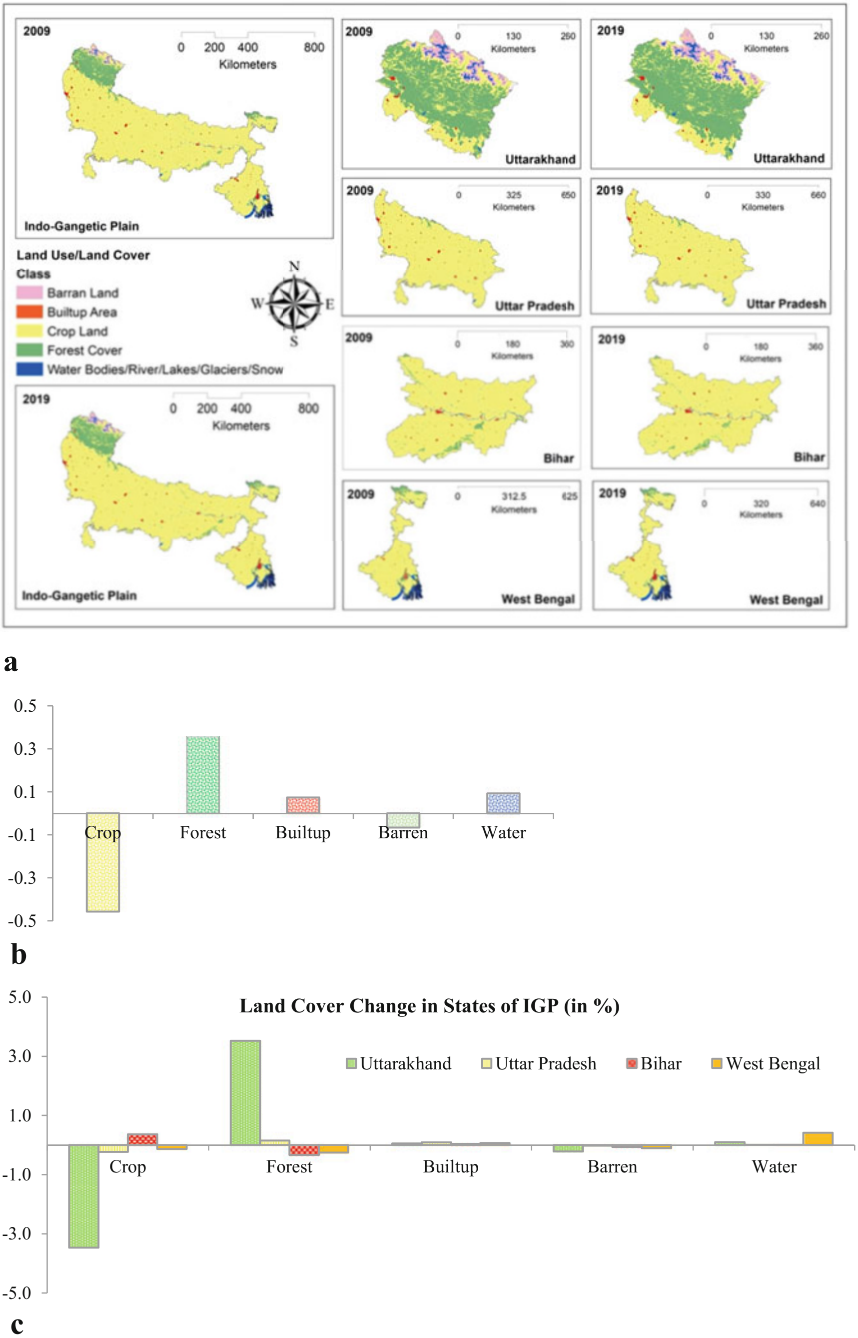

Fig. 4.7 (**a**) Land use/land cover map for states of Indo-Gangetic plain. (**b**) Land cover change in the IGP (in %). (**c**) Land cover change in states of region (in %)

Table 4.11 Total forest cover in Uttarakhand, UP, Bihar, and West Bengal from 2011 to 2019 (Source: ISFR)

Year	Total forest cover (km^2)			
	Uttarakhand	UP	Bihar	West Bengal
2011	24,496	14,338	6845	12,995
2013	24,508	14,349	7291	16,805
2015	24,272	14,401	7254	16,826
2017	24,295	14,679	7299	16,847
2019	24,303	14,806	7306	16,902

the region by 0.35% (1719 km^2). Results clearly show that the built-up area increased by 355 km^2 due to rapid development in infrastructure.

The state-wise data of forest cover were collected from the Indian State of Forests Report of the years 2011, 2013, 2015, 2017, and 2019 and tabulated (Table 4.11). In the 2017 report, the values for forest cover given in the 2015 report were updated. To have a fair and accurate reflection of the change in forest cover, the updated data for 2015 are used, as given in the 2017 report (ISFR 2011–2019).

The cover of forest under the very dense category has increased in all four states over the years. Overall, the forest cover in the states examined has remained consistent except for West Bengal. In West Bengal, an increase of 3907 km^2 can be noted. Since 2013, TOF (Trees Outside Forests) areas have been included in the report in Bihar and West Bengal. This is used to explain some of the sudden increase in the forest covered area in these states.

In Uttarakhand, from 2011 to 2019, the area under forest cover has reduced by 193 km^2. In 2015, a negative change of 236 km^2 forest was observed. The ISFR attributes these changes mainly to rotational felling and the diversion of forest land to developmental activities. Under the Forest Conservation Act, 1980, from 2015 to 2019, 2850.87 ha (28.5087 km^2) of forest was diverted for nonforestry purposes. Forest cover in Uttarakhand, as stated in the 2019 report, is 24303.04 km^2. Forest covers 45.44% of the total geographical area of the state. Out of the recorded forest area (RFA) of 38,000 km^2, 26,547 km^2 is categorized as reserved forest. Compared to the ISFR 2017, there has been a 78 km^2 increase in the "very dense" forest area while "moderately dense" forest area has been reduced by 79 km^2. Open forest gained an area of 9 km^2 since the last report. A net increase of 8 km^2 of forest cover was reported in the 2019 report. According to ISFR 2019, the increase is a result of both plantations and conservation activity (ISFR 2011–2019).

In Uttar Pradesh, since 2011, the trend in forest cover change has been positive. In 2017, a positive change of 278 km^2 in forest cover was observed. The ISFR 2017 again attributes this to plantation activities and conservation efforts. The forest cover of the state, reported in the ISFR 2019, is 14,805 km^2. This constitutes 6.15% of the total geographical area of the state of Uttar Pradesh. Out of this, 2616.43 km^2 is under very dense forest. Moderately dense forest covers 4080.04 km^2 of area while open forest covers 8109.08 km^2. A net increase of 126.65 km^2 of forest cover has been observed since the report in 2017. The increase in forest cover can be attributed to plantation activities carried out in the state in recent years. In 2019, under the

Vriksharopan Mahakumbh Program, more than 22.5 crores of saplings were planted in the state during the plantation season.

The increase in forest cover area in 2013 in Bihar is explained by the inclusion of TOF area in that year's report. This increase was also attributed to afforestation in the ISF Report of 2013. According to the Indian State of Forests Report 2019, 7.76% of total geographical area in Bihar is under forest cover. A total of 7305.99 km^2 of land is under this description. A net positive change of 6.99 km^2 in forest cover is reported in ISFR 2019. Tree cover decreased by 260 km^2 as compared to ISFR 2017.

4.4 The Study on Impacts of Nitrogen Pollution of Forests Adjoining the IGP in Himalayas

One of the Work Packages (3.1) of South Asia Nitrogen Hub (SANH) is to study the impacts of nitrogen pollution of forests adjoining the IGP in the Himalaya. Impacts are often delimited to assessing the parameters of forest vegetation such as tree density, stratification, overall photosynthetic viability of mature as well as saplings, sapling viability, etc. None of these are indicators of forest health but are merely parameters to be monitored to identify whether a problem exists or is emerging. The vegetational parameters like the EVI and NDVI, described earlier, also point toward the overall improvement or degradation of forests. Lichens, a symbiotic association between algae (or cyanobacteria) and fungi are highly sensitive to pollution. In both Europe and the U.S., lichens have been included as indicators of forest health (Galloway 1992; Stolte 1997; Wolseley et al. 2006; Lalley et al. 2006 Pinho et al. 2012; Munzi et al. 2013; Nascimbene et al. 2013, Will-Wolf et al. 2015; Munzi et al. 2019; McMullin et al. 2016; Filippini et al. 2020; Czerepko et al. 2021). The South Asia Nitrogen Hub (SANH) Work Package (WP3.1) is therefore studying the impacts of pollution on select species that are important as a nontimber forest product, and potentially nitrogen-sensitive (*Everniastrum*, *Parmeloids, Parmotrema, Ramalina,* and *Usnea*sps) being species preferred in trade and providing livelihood support to local communities (Chatterjee et al. 2017).

The lichen vegetation in the IGP and its catchment is controlled by two factors (1) the natural gradients of topography and climate, and (2) the zoo-anthropogenic gradients (Upreti 1998; Rai et al. 2012a, b; Shukla et al. 2016). The vegetational gradients in the catchment area of the Ganga, i.e., in the Himalayas (Singh and Singh 1987), create variability in the forms of lichens, where in the foothills crustose and tolerant lichens dominate, followed by larger foliose, fruticose, and dimorphic forms at higher elevations (Upreti 1998; Rai et al. 2012a, b). This natural variation in community dynamics of Himalayan lichens is highly influenced by the land use and associated pollution gradients created by various ambient air pollutants such as heavy metals, polycyclic heavy metals, and ammonia-nitrogen gradient (Shukla and Upreti 2007a, b; Shukla and Upreti 2009; Shukla and Upreti 2008, 2009, 2011; Khare et al. 2019; Rai et al. 2011, 2012a, b, 2013, 2014, 2016, 2020; Nag et al. 2012, 2019). Studies done so far have concluded that unsustainable utilization of forest timber and nontimber produce has negatively affected the Himalayan forests, resulting in thinning of dense forests (Upreti 1995; Upreti et al. 2005; Nag et al. 2012). Lichens act as integrated early warning systems for the status of forest health (McDermott 2016). Based on a statewide study in the Gangetic catchment of the state of Uttarakhand, indicator species of lichens were identified which can act as early warning system for the Himalayan forests (Rai and Gupta 2015).

The number of lichen species, known from the different states in the GP, i.e., Uttar Pradesh (156 species), Bihar (156 species), and West Bengal (753), indicate the collection effort, but also on the other hand indicate forest cover and health (Sinha 2021). Though there are very few studies on lichens, they all show the derogatory effect of pollution loads the IGP face due to intense urbanization, industrialization, and agricultural activities (Saxena et al. 2007; Satya and Upreti 2009; Satya et al. 2012; Majumder et al. 2012; Sharma et al. 2018, 2019). The studies have thus far identified that some lichens such as *Pyxinecocoes*, *Peltula, Rinodinasophodes* can act as an indicator of forest health in the IGP (Karakoti et al. 2013; Sharma et al. 2018, 2019).

4.5 Discussion

The Gangetic plains include the densely populated states of India, Uttarakhand, Uttar Pradesh, Bihar, and West Bengal, which are primarily agricultural and have witnessed land degradation in the past. There have been reports of forest die back and attacks by insects and pests in the region, and impacts require survey, documentation, analysis, and remediation.

The present initiative of TERI SAS under the aegis of SANH is specifically looking at the raised concentrations of NH_3 in the forests adjoining Indo-Gangetic plains (Van Damme et al. 2018). Sutton et al. (2020) have expressed concern over alkaline air, with NH_3 being the most significant component, largely due to agricultural application of fertilizers and livestock manure. The residence time of ammonia is short in the atmosphere and there are reports of deposition in terrestrial and aquatic ecosystems. In combination with other gases like SOx and the NOx, ammonia also contributes to the PM2.5.

Furthermore, a Global Nitrogen Assessment is underway by the International Nitrogen Initiative and the International Nitrogen Management System (INMS) supported by the Global Environmental Facility (GEF). The Indian Nitrogen Assessment (2017) provides an account of nitrogen in agro-forestry, horticulture, freshwater marine and brackish water aquaculture, and freshwater ecosystems and with respect to energy and industrial sectors in India. Impacts of pollution due to ammonia, in conjunction with other pollutants, are under investigation. Consumption of nitrogen in India has increased from 0.6 Mt in 1965–1966 to 17.4 Mt in 2015–2016 with a use efficiency of 32–35% (Swaminathan 2017).

The declining trend of the vegetation indices observed in this study cannot be ascribed to the levels of pollution. Our land use land cover shows rather a decadal increase in forest cover by 0.035%. Our findings gel with the Biannual Forest Cover Reports of Forest Survey of India for the period 2009–2019.

While the present chapter has focused largely on four states (GP) on the IGP, SANH's wider endeavor is to study the impacts of pollution with a focus on nitrogen in South Asia with lichens as an indicator. The study is being conducted in Afghanistan, Pakistan, India, Nepal, Bhutan, and Sri Lanka with support from the Global Challenge Research Fund (GCRF) United Kingdom Research Innovation (UKRI) and coordinated by Center for Ecology and Hydrology, UK. Studies are presently being conducted on nitrogen deposition, tissue damage to lichen thalli, chlorophyll content of the lichens, pH of the bark of trees which hosts the epiphytic lichens, nitrate content, and conductivity of soil as indicators.

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Understanding Wildfires and Designing a Sustainable Future by Solutions Based on Forest-Society Relationships

5

Fernando Prieto and Máximo Florín

Abstract

Wildfire features effect about 4 million km^2 of land throughout the world every fire season. This is a global issue, especially in Mediterranean regions, where provision, regulation, and cultural ecosystem services are threatened (e.g., 8.2 million has burned between 1961 and 2021 in Spain), which are worldwide biodiversity hotspots; besides, their summer is also the dry season and is becoming longer and more intense with climate change, increasing the potential risk of fires in these areas. Social and economic changes were sharp over the last decades in forested regions. However, is not wise to lose forest areas of high ecological value. Restoring woodlands takes between a few and many decades, and it involves a large amount of money. Instead, it is more logical to carry out preventive planning, and it creates new jobs in rural areas. This paper addresses these problems by seeking proposals based on forest-society relations. It aims especially at: (1) a novel compilation of the extent and time dynamics of forest fires and their main types, together with their relationships with the main weather, biogeochemical, and plant community aspects on a representative case study, (2) the international, i.e., Mediterranean, scope, and decennial evolution of the surface affected by forest fires both in absolute terms and as a proportion of the total forest area, and (3) integrate the implications of social and economic factors and forest policies.

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Keywords

Sustainability · The Mediterranean region · Socioeconomic · Forest fire · Ecosystem

5.1 Introduction

Mediterranean brushlands and forests appear in ecoregions throughout four continents. The Mediterranean basin is their major focus, besides those of Chile, California, South Africa, and Australia. These ecoregions occupy less than 2% of our planet's surface. However, they are home to about 10% of all the world's species (Valavanidis and Vlachogianni 2013). So, the Mediterranean basin harbors over twice as many woody plants as non-Mediterranean Europe (Gauquelin et al. 2018). Such a high biodiversity results from biogeographical events, anthropic management, and geographic and climatic contrasts which have been acting together since almost 6 million years ago. Forests and scrublands vary a lot. Sclerophyllous and evergreen woody plants dominate them, but also include malacophyllous and deciduous ones. The same applies to woody vegetation communities, which range from forests to preforest succession stages, with lower density and height. These stands of woody vegetation are very productive when in good condition. This makes their ecosystem services, i.e., provisioning, regulating, and cultural, even more remarkable. As a paradox, Mediterranean regions are among the most threatened in the world by global change and by the prolonged anthropical influence and its recent intensification.

Forest fires cause serious environmental, economic, and social problems every summer, including social alarm in the affected regions. Fire is a common organizing factor in forest ecosystems, but we must control its extent, intensity, and frequency when they reach great magnitude, as in recent years. Since 1961, when reliable statistics are available, 30.3% of the forest area in Spain has burned, representing 16.4% of the country's surface area, but its frequency per hectare varies, as some forest ecosystems have burned several times and others only once. The burning of these extensive areas has serious ecological, economic, and social consequences, such as significant greenhouse gas emissions, changes in water flows, soil erosion, population displacement, landscape degradation, and loss of biodiversity, all affecting forest ecosystem services, goods, and basic materials for the forest sector (Wunder et al. 2021). Although Prieto (1995) already noted it some time ago, forest policies have not adequately addressed this problem most times, especially in Mediterranean countries, since they hardly take fire prevention into account and consider fire as an unpredictable event, even if it repeats year after year regularly. As many of the author's data and conclusions remain ignored, it is still necessary to analyze the dynamics for decades with updated information. When prevention does not take place, it is too late to detect wildfires, and the means of detection are never sufficient; the only option left is to extinguish them and prepare for the next season's likely catastrophe. The extensive area affected, together with the loss of human lives and economic ruin, shows the huge scale of the threat and the necessity to revise the forest management strategies currently in place. Under the present Intergovernmental Panel on Climate Change's scenarios, recurrent droughts, and inadequate policies (Calheiros et al. 2021), the prognosis for the not too distant future is more than disturbing. Examples of specific factors that, jointly and/or separately, will increase the risk of fire are (1) more often extreme weather events, i.e., irregular rainfall, increased heat waves, long and intense droughts, and (2) lack of forest management and traditional exploitation, e.g., with the help of cattle, firewood collection, water harvesting, etc. The harshness of the tragedy hit, for example, Portugal in 2017, where a single massive fire of eucalyptus and maritime pines caused over 120 deaths and 40,000 ha burned. The only alternative is to prevent fires, mitigate their effects, and carry out maintenance work on woody stands, especially those with the greatest problems in adapting to the consequences of climate change and the intensification and accumulation of changes in land use. This joint action has many potential economic benefits, because it contributes to creating jobs that are stable in the forestry sector and promotes the so-called "green jobs strategy", which includes valuing biodiversity as a basis for a healthy humanity and viable economic development, in line with the guidelines of the Organization for Economic Cooperation and Development (OECD/Cedefop 2014). Therefore, the objectives of this work are:

1. To review the extension and time dynamics of forest fires and their major types under main weather, biogeochemical, and plant communities' contexts in a representative case study, i.e., Spain, dealing with new data and old data of limited availability.
2. To explore the international, i.e., Mediterranean scope, and decennial evolution of the surface affected by forest fires in both absolute terms and proportion to the total forest surface.
3. To analyze the integrated implications of social and economic factors and forest policies.
4. To describe proposals for a sustainable forestry future by solutions that are based on forest-society relationships.

5.2 Case Study: Historical Trends in Spain

As stated above, the fire crisis in Spain reflects the threats and dangers we are currently facing worldwide, in terms of trends, policies, and related socioeconomic aspects. Figure 5.1 details the strong irregularity of forest fires in Spain, with 4 years since 1961 in which over 400,000 ha of forests burned. So far, in the twenty-first century, over 200,000 ha have burned in 3 years. This trend is likely to be repeated in the medium term if woody vegetation ecosystems continue to be managed in an unsustainable manner (Prieto 1995).

Since there are no models that predict the area of woody vegetation communities that will burn each year, the question arises: what happens in a particular year? For example, because of the drought in much of the country, one would expect that 2017

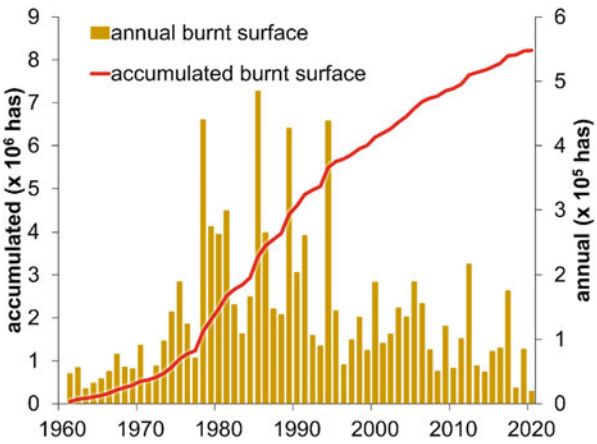

Fig. 5.1 Dynamics of the surface affected by forest fires in Spain over 1961–2020. Prepared by Observatorio de la Sostenibilidad with data from Ministerio de Agricultura, Pesca y Alimentación (2021a)

would be a problematic year. As of July 3, 56,000 ha had already burned, while 10,000 ha burned in the same period of the previous year. The expected number of fires were around 10,000, of which 20 would exceed 500 ha (i.e., Large Forest Fires—LFF), a few would exceed 2000, and one would even reach 10,000. The predicted affected area exceeded 100,000 ha, but reality overcame this prediction (Fig. 5.1). During 1994 (one of the most terrible years), 437,635 ha burned in Spain, with almost 20,000 fires. The number of deaths in fires were 36, 27 of them in firefighting activities (firefighters, aircraft pilots, etc.). The main fires occurred in the Eastern Iberian Peninsula, but undoubtedly the most impressive and ravaging fires occurred in two Catalan areas (the first to be attributed that year to the poor state of a high voltage line); 45,000 ha burned in a few days (3% of Catalonian forest area). However, in the Valencian Community, it was even more dreadful, since 11% of its forest area burned, and communities of great ecological value had already burned in the latter campaigns. The geographic heterogeneity of fire incidence varies over time depending on the particularities of the climate, although these conditions do not allow us to understand the process in its entirety (Bradstock 2010). Droughts of similar magnitude can accompany large fires and extensive burned areas (i.e., the third quarter of the 1980s, first third and the late 1990s), or not (i.e., the second third of the 2000s). The casuistry is diverse and complex, but when drier periods and the absence of prevention and vigilance concur in certain areas, fires reach dramatic proportions. Extreme annual values of the burned area such as those shown in Fig. 5.1 may return in future seasons. Large forest fires (LFFs), i.e., those burning over 500 ha, are also a major contributor to the problem (Fig. 5.2). On one side, they are less abundant than the rest of the fires. However, they involve maximum danger, public alarm, and death and economic toll. Statistics attribute 60% of the forest surface that burns each year to between 5 and 65 fires.

Although the number of LFFs have decreased since the 1990s, the area burned by LFFs has increased. According to Pellegrini et al. (2021), regions with arid seasons, such as the Mediterranean, are the most sensitive to changes in fire frequency. These

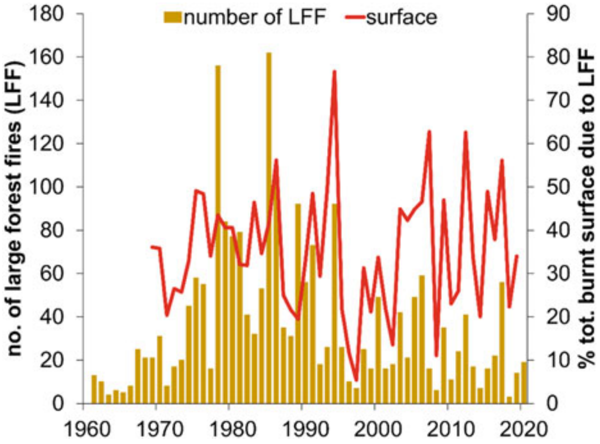

Fig. 5.2 The dynamics of large forest fires in Spain. Prepared by Observatorio de la Sostenibilidad with data from Ministerio de Agricultura, Pesca y Alimentación (2021a)

authors observed that common characteristics of woodland plots that burn more often are (1) tree biomass-dominated stands with poor N and P content, and (2) an efficient symbiotic uptake of N. The recurrence of fires over time has obvious implications on the pattern and the conformation of tree communities, while the importance of long-term variations depends on the meteorology, the profile of the vegetation formation, and the precedents of the fires. Ultimately, the influence of the forest fire pattern we are experiencing now will be explicit in the coming decades and will affect C accumulation and N and P recycling in the coming future. The same applies to the extent of forest fires, as the magnitude, frequency, and time since the preceding disturbance has all analogous effects on Mediterranean communities. Dominant wood species are key in shaping the structure and composition of forests, as well as on nutrient cycling, soil fixation, or the amount of light they allow to pass through. Therefore, they are determinants of the courtship of shrubs and other species in forest ecosystems, but also regarding forest fires.

Trees like eucalyptus and pine burn more than other woody taxa, relative to their cover surface (Fig. 5.3). In the north of the Iberian Peninsula, pines and eucalyptus (the latter coming from Australia) form forest crops. They are not native species of that territory, but planted only for production. These areas have burned with more frequency, intensity, and magnitude than other areas.

Wet climate protects rainy regions against wildfires, e.g., the Basque Country. However, its monoculture stands of Monterey pine, which was introduced from California, favored LFFs in periods of drought and strong winds, i.e., in 1989.

On the Mediterranean coast and extensive areas in the center of the Iberian Peninsula, forest fires have affected especially those reforested with Aleppo pine that has a high propensity to burn. Stands which suffered most from wildfires in the 2000s included just three species. These were Aleppo pine, in 27% of the cases, common eucalyptus (about 14%), and maritime pine (over 11%). In contrast, holm-oak stands occupy a larger area, but accounted for a significantly lower percentage of the burnt area (7.59%), according to Ecologistas en Acción (2016).

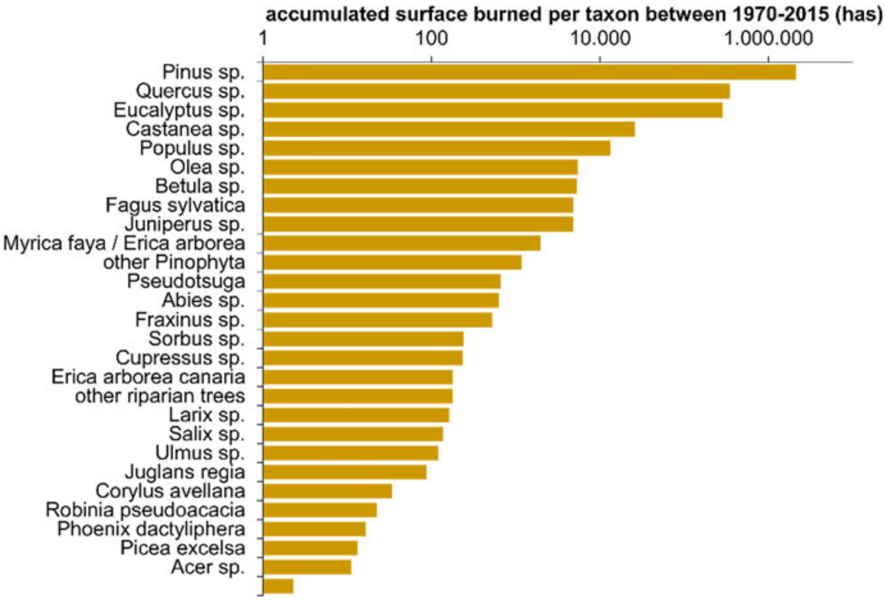

Fig. 5.3 Accumulated surface burned per tree taxon between 1970 and 2015. Prepared by Observatorio de la Sostenibilidad. Source: Ministerio de Agricultura, Pesca y Alimentación (2021a)

Looking at the proportion of the area burned in large fires by taxa (Fig. 5.3) confirms that pattern. This is because eucalyptus and pine trees are more likely to burn compared to others. The uncontrolled and contiguous monoculture of their woody stands enhances the frequency and extent of fire. It occurs also in other Mediterranean ecoregions. This was the case of the Monterey pine plantations in the Chilean ecoregion in 2016, or the stands of pine and eucalyptus that large fires ravaged over Portugal in 2017.

As prevalent trees in a woody stand contribute to determine its likelihood to burn, changing vegetation structure and composition can help reduce wildfires. Promoting species and stands less prone to burning is a priority over, for example, eucalyptus and some conifers such as maritime or Aleppo pines, which are most susceptible to burning. However, this has not been the practice for over seven decades; rather, the two major drivers of the increase in the wooded area in Spain have been (1) the secondary succession in abandoned crop fields, and (2) woody plantations. The species selected for the latter were mainly fast-growing trees covering about 90% of the total area of woody plantations (Table 5.1).

Wildfires affect nature reserves that exist only on paper. This is a constant all throughout Spain, from the Atlantic massifs of the northwestern Iberian Peninsula to the Mediterranean shrub garrigues of the Balearic Islands. For instance, forest fires were abundant in 2017, but the most important one occurred in the internationally iconic Doñana National Park and UNESCO Biosphere Reserve. Over 10,000 ha burnt, that means 18% of its protected natural surface. This had serious impacts on

Table 5.1 Surface of woody plantations of the main species in Spain, in absolute value and percent of total, according to different sources and periods. *FNP* inventory of the forestry national plan, *FM* forestry map, and *FS* forestry statistics

Source	FNP 1940–1965		FM 1966		FS 1879–1997		FM 1997	
Species	Has	%	Has	%	Has	%	Has	%
Maritime pine	329,664	27.83	413,384	26.29	730,865	20.58	1,045,375	24.87
Aleppo pine	195,510	16.50	281,213	17.88	518,273	14.59	450,736	10.72
Europe red pine	241,966	20.42	301,716	19.19	515,857	14.52	524,329	12.47
Eucalyptus spp.	91,955	7.76	208,364	13.25	415,502	11.70	845,100	20.10
Black pine	153,306	12.94	142,414	9.06	364,145	10.25	278,615	6.63
Ital. Stone pine	84,737	7.15	66,489	4.23	253,556	7.14	235,340	5.60
Monterey pine	55,442	4.68	142,681	9.07	188,710	5.31	363,466	8.65
Other species	32,114	2.72	16,141	1.03	564,950	15.91	460,861	10.96
Total	1,184,694		1,572,402		3,551,858		4,203,822	

wildlife, including the population of the Iberian lynx, the world's most endangered cat species. Forest planning was once again conspicuous by its absence.

Another source of the sharp increase in fire prospects due to forest mismanagement is a poor practice that is currently becoming more and more common. It is the massive tree plantations in areas where they grow quickly, reportedly to "mitigate climate change". Instead, sustainable forest planning should consider the eventual variations in the intensity and frequency of fires that would affect those stands over the long term (Pellegrini et al. 2021).

5.3 International Comparison Among Mediterranean Countries

The Spanish situation of forest fires is not singular in the world. Indeed, it is especially extrapollable within the same climate domain. Comparison with other Mediterranean countries shows similar patterns and incidence of wildfires over decades (Table 5.2). The Iberian Peninsula holds the relative and absolute records for hectares burned, i.e., 65% of the total forested area in Portugal and almost 6000 square kilometers in Spain.

Table 5.2 The dynamics of burnt hectares of forest (gross and percent of total forest surface) in the Southern European countries[a]

Period average/ total	Portugal	Spain	France	Italy	Greece	Total
Average 1980s	73,484	244,788	39,157	147,150	52,417	556,995
Average 1990s	102,203	126,319	22,735	118,573	44,108	448,938
Average 2000s	150,101	127,229	22,362	83,878	49,238	432,809
Average 2000–2015	92,377	98,660	8947	59,435	29,609	288,937
Average 1980–2015	105,893	164,592	24,895	107,002	45,424	447,807
Total 1980–2015	3,812,148	5,925,323	896,216	3,852,072	1,635,277	16,121,036
Total forest surface[b]	5,907,000	27,627,000	17,579,000	11,110,000	7,546,000	52,207,579
Total % affected	65%	21%	5%	35%	22%	31%

[a] Ortuño (2012)

[b] SanMiguel-Ayanz et al. (2016)

Wildfires affected an extensive forestry surface of the Mediterranean region of Europe over 30 years. In only five south-European countries, 161,210 km^2 burned, reaching 31% of their total forested surface. The situation worsens as global temperature and droughts' frequency, intensity, and duration increase (Peñuelas and Sardans 2021). This was the case, for example, of the catastrophic wildfires of the twenty-first century in California, Australia, and Portugal, the latter with a record of 500,000 ha burned and over 120 casualties in 2017. Dealing with these trends and perspectives is a colossal challenge; it requires a transition to new management models, policies, and land use planning, and should pay attention to forest ecosystem services and trade-offs in the light of climate emergency (Fernandez-Anez et al. 2021).

5.4 A Broken Balance in Three Generations

A major problem over time in addressing wildfire issues is the stubborn neglect of social and economic systems and their dynamics. The urban legend that wildfires are only a matter of arsonists still requires too many didactics (Bradstock 2010). Climatic, use, cultural, and socio-economic conditions modulate forest diversity. Humans have transformed European forest systems over thousands of years, particularly in its south. In contrast, degradation of North American forests, for example, only began two centuries ago.

The strong interplay between people and forest in Mediterranean ecoregions sharply changed in about 75 years. The latter three generations are witnessing the aging, the decline in number, and change in habits of people living in the mountain and forested areas (Prieto 2014). The Spanish population of rural areas has gone from 4.9 million in 1940 to 1.7 million in 2010. Firewood collection has decreased to 14% between 1960s and 2000s, and from 9946 thousand tons to 2445 until 2010. The resin gathering also went to 6% between 1966 and 2000. The same is valid for other forest commodities, such as bark, nuts, pinions or *esparto* fiber, showing the underutilization of forest products (Table 5.3).

Extensive cattle raising, that once regulated scrubland and pastures, is still vanishing from vast parts of the landscape. This follows poor profits and insufficient aid, and it is especially true in the highlands. The consequence is the neglect of

Table 5.3 Production of nontimber forestry commodities in Spain (in thousands of tons)

Period	Cork	Resin	Chestnuts	Pinions
2010s	61.5	2.5	35	2.5
2000s	59.2	2.9	40	3.0
1990s	73.8	10.6	40	3.0
1980s	75.9	26.3	50	3.5
1970s	109.5	43.1	60	3.5
1960s	11.6	54.1	70	4.5

Source: Ministerio de Agricultura, Pesca y Alimentación (1960–1990, 2021b), Ortuño (2012) farming and grazing areas within woody stands. Finally, interspersed fields that caused discontinuities within those land mosaics become areas of continuous scrubland.

Spain applied an incorrect silviculture strategy between the 60s and the 80s. It comprised massive monocultures of a few taxa, namely conifers and blue gum. Three million hectares of them were tree plantations. As noted above, these stands present high fire risk. In addition, the care of these stands was nonexistent. In parallel, the Land Act allowed to develop infrastructures and urban areas in forests, eventually fragmenting and damaging them.

The political transition to democracy and regional self-government brought with it many new nature reserves. They accounted for up to 40% of Spain's total forest area. But their planning and monitoring were absent from this conservation rush, as were allocations for their maintenance. Even the Natura 2000 Network of the European Union includes many of these reserves, but they have no land use strategies either. Worse still, their declaration prohibited traditional activities, including firewood collection, grazing, etc. These practices could have contributed to their stewardship by improving the social perception of the new protected areas. The burning of almost a fifth of the surface of the Doñana Biosphere Reserve in 2017 was the allegory of failing to detect and prevent fires, and plan the management in Spain's most interesting forest ecosystems.

Several tendencies persist at present. For instance, natural or planted forests stands, together with the wood, cork, and paper industry, yielded a GVA (i.e., Gross Value Added) to the forestry sector of over €5 million in 2014, almost 8% less than in 2013. Average employment in these occupations was 134,200 people in 2016, 2.6% less than in 2015 (MAPAMA—Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente 2017).

All these factors highlight the poor stewardship of forests. Their result is the accumulation of large stocks of flammable forest biomass (brush, wood, unused pastures, etc.). Besides, their pattern of disposal is continuous, which makes ecosystems vulnerable. In the long run, any lightning, the spark, carelessness, negligence or intentional action have the potential to trigger fires that are difficult to extinguish. The traditional model of forest management and use, maintained for over 2000 years, has suffered a drastic abandonment in just 60 years. The balance of the man-livestock-forest system has collapsed, and burning is a symptom of that problem.

This has joined to a inadequate forestry and agricultural policy, which have not carried out (1) adequate silvicultural treatments or promoted the management of forest stands, (2) nor actions to reduce the flammable biomass stocks with, e.g., extensive cattle ranching, or to extract them with science-based procedures (Prieto 1995).

Fire detection is in the same time neglected. Hundreds of watchtowers are empty or have reduced schedules of even a couple of months each year. The periods of fire risk eventually occur in seasons of inactivity when no one is there. Vigilance patrols, which are supposed to cover the forests thoroughly, are scarce. Nor is there any precaution linked to the efficient use of forest ecosystems. Work contracts are precarious, workers lack specialized training, and there are no cattle or forestry work. This creates a context with a very high fire risk. If it starts, extinguishing it becomes very complicated most of the time, if it is possible at all.

In coastal watersheds, planning and land use policies give priority to seaside tourism and urban development, with upstream countryside areas being excluded from facilities and care. This uneven stewardship drives an intensification of social and economic shifts that lead to a landscape's heterogeneity in structure and a shrinkage of the traditional means of subsistence of the rural population. The incessant conflict of interest among stakeholders triggers dramatic trade-offs between land use, the environment, and the economy (Salhi et al. 2021).

Public resources continue to prioritize extinction, while neglect detection and prevention. Estimated extinction expense accounts for 64% of the firefighting budget, 13% of restoration expenditure, and 23% of prevention costs (Hernández 2014). Various thousands of firefighters and forest agents struggle every year, often at serious risk to their lives, trying to control an often uncontrollable phenomenon. If extinguishing does not begin in a matter of minutes, its efficacy becomes minimal. Forest fires that spread from crown to crown can reach a dozen meters in height and from several hundred meters to even kilometers. If they do not arrive in the first few seconds, aircrafts have very limited effectiveness with their five tons of water. In summary, policies for the back country and woodlands failed to consider the burning factor prior to their design or application.

Public opinion perceives fires as one of the main environmental problems in Spain, according to official sociological studies cited by the Ministerio de Agricultura, Alimentación y Medio Ambiente (2014).

Specifically, the Ecology and Environment studies carried out by the Centro de Investigaciones Sociológicas (CIS 1996, 2005, 2007) between 1996 and 2007 rank wildfires as an outstanding natural concern, with respondents ranking it as one of the first response choices (1996: 81% and 2005: 77%). In addition, their ranking of the top environmental problems perceived in their immediate environment, nationally and globally, places deforestation as one of the main global concerns.

However, citizenship has not acknowledged the significant benefit and critical role of green infrastructure for the time ahead, especially in climate change (Vilar et al. 2021).

5.5 Proposals for a Sustainable Forestry Future

The solution lies in a new policy, which should focus on concrete measures (Prieto 2015) aimed at fixing people and jobs in the forests' industry, incorporating regional development and protecting ecosystems.

1. Rural abandonment of the last 50 years must cease, revitalizing the environment with a population that inhabits it, taking profit from the farming and cattle raising potential, as well as taking care of the woodlands.

2. Renew the forestry strategy upon the fight against rural depopulation, securing jobs in the sector, and promoting the value of forest habitats as shared assets.
3. Never forget again to act in private forests where, most of the time, prevention is lacking. This should integrate economic, social, and ecological values in the National Accounts, allowing forestry and conservation services to share in the profits they generate. These are inversions that will fix the people and create jobs.
4. Reuse forest mosaics, giving a dignified life to the people who want to live in this landscape.
5. To perform a distinct valley-to-valley and mountain range-to-mountain range administration, increasing the small budgets allocated with adequate programming.
6. Paying due attention to green infrastructure, which is at the heart of fundamental productive change, according to the EU, instead of continuing to allocate public resources solely to gray (i.e., concrete) infrastructure, such as major highways or high-speed rail.
7. Recover the function of traditional cattle ranching, but only after supervising it, in the preservation and clearing of the woods.
8. Active management throughout the year and prevention and extreme vigilance during periods of danger will save on extinction.
9. Controlled burning by forestry agencies, the transformation of juvenile and closed woodlands in high mountain areas, and the creation of pastures or mosaics have proven to be effective preventive measures. Forest formation lasts from decades to centuries, but its loss by fire or logging takes only minutes. Hence, we must act beyond those instants and preserve what is so fragile and yet so essential for everyone.
10. Governance will also have to conform to these principles. For example, the Forestry Law of July 20, 2015 unprotected burned areas and took powers away from forestry agents, and this proved to be a wrong thing to do.
11. Incorporate the principles of global climatic changes and biological diversity in managing of forest ecosystems, and ensure that forest policies change in the coming five decades.
12. Change and relearn to value the role of social and political sensitivity to forest ecosystems.
13. There must be a personal bond between people living in forest areas assuming that it is necessary to preserve them.
14. Society and politicians should value forest ecosystems as common resources. They produce timber, fuelwood, fine meats, beekeeping, etc., and they ensure essential forest ecological functions such as fresh water provision, protection against desertification, microclimate enhancement, biodiversity maintenance, etc.

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Is the Gender Agenda of Nepal's Community Forestry at Risk due to Commercial Transitions?

6

Kalpana Giri

Abstract

For the last 40 years, community forestry in Nepal is widely recognized for its participatory forest co-management model with an emphatic focus on gender equality. The program has established women's roles and leadership in public spheres of forest management, which, in turn, has led to sustainable stock and governance of forests. Despite its legacy, conversations on gender equality have become challenging in the current transitions to commercial forestry in Nepal. With mature forest stocks in place, there is an ongoing discourse on shifting from subsistence to commercial models of forest management across community forests, especially in the ones with the high-earning potential. The current discourse around the economic growth-centric slogan—"Forestry for Prosperity"—has largely misinterpreted gender agenda as an obstacle to achieving prosperity. Using literature review and interviews with key experts, this paper examines the reasons behind such framing and identifies its implications to gender agenda in community forestry. Some suggestions to revitalize the gender agenda are provided, such as by accounting economic costs of forest management and positioning women and marginalized groups in new economic roles.

Keywords

Commercial forest management · Subsistence · Social norms · Gender roles · Prosperity · Resistance

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6.1 Introduction

Community forestry (CF)[1] models have been initiated in the region since the mid-1980s as effective responses to curb deforestation, reduce state budget on conservation, and garner legitimacy for government policies through public participation (Sunderlin et al. 2008). Nepal is considered one of the pioneer countries that adopted the community forestry program some 40 years ago within the context of Himalayan degradation, subsistence economy, and forest-dependent communities. The program runs through a co-management model wherein communities have rights to use, manage, and benefit from forest management. The community forestry model is now widely recognized, adopted, and valued for its potential to yield multiple positive outcomes for ecological conservation, livelihoods, community rights, and gender equality (Ojha et al. 2009). Currently, the program's scope is enormous spanning over 40% of total forests and managed through 22,226 community forest user groups.[2]

Community forestry is also known for its explicit policy and institutional provisions on the gender equality agenda. Women's roles and gender equality agenda have been clearly recognized in the program. Several policy precedents and institutional provisions of the program mandate equal (50%) representation of women and men in decision-making positions and inclusive arrangements for benefits sharing. Gender and community forestry is one of the well-researched topics. Studies have indicated the prevalence of gender-differentiated knowledge, roles, and needs of women and men in forest management (Lama and Buchy 2002). They have also examined gender distribution of leadership and benefits sharing in the program and have identified mechanisms through which gender gaps and power relations are perpetuated and reframed (Agarwal 2010; Nightingale 2006; Pokharel and Tiwari 2013; Chhetri et al. 2013). There is also a fair amount of research evidence that confirms a positive relationship between women's presence in decision-making spaces with better decision-making for forest governance (Agarwal 2010; Bhandari et al. 2018; Leone 2019). In addition to positive impacts on forest governance, community forestry has enabled women's leadership in public spheres of decision-making and political participation in state mechanisms (Giri and Darnhofer 2010; RRI 2018). And yet, women's control over decision-making remains limited. Decision-making is retained by male members (Chhetri et al. 2013). Informal institutions, rulemaking, and social and structural status quo that favor and privilege men continue to act as barriers for women to access to and ensure control over forest management decisions (Khadka et al. 2014; Wagle et al. 2017; Bhattarai 2020). These studies contend that seemingly inclusive and participatory

[1]Community forestry refers to a wider umbrella term that includes initiatives, science, policies, institutions, and processes that are intended to increase the role of local people in governing and managing forest resources. In case of Nepal, community forestry is also a designated name for a co-management model wherein local communities are responsible for sustainably managing, protecting, and using forest resources within the scope of legal laws and guidelines.

[2]Unpublished data from the Ministry of Forests and Environment, December 2020.

mechanisms focusing on the forest sector alone are insufficient to redress discriminatory gendered power relations that stem from social and structural inequalities planted in Nepalese society.

Concomitantly, Nepal is going through rapid economic and social transitions characterized by urbanization, migration, and changes in political governance. The forest condition and stock of community forests have also changed. With mature forest stocks in place, there is an ongoing discourse on shifting from subsistence to commercial models of forest management in CF, especially in high-earning community forest user groups. These emerging transitions have not only altered forest–people relationships, but it has also initiated discussions on new commercial modalities of CF that would fit with the changing context of Nepal. These discussions have also started to impact the gender agenda of community forestry. This chapter explores the questions of whether and how gender agendas are placed and discussed in the commercial transitions related to forest management? It identifies gender agendas and their associated positioning in the ongoing transitions and assesses prospective implications of these transitions for women's rights and equality in community forestry. It also identifies some options for policy, institutional mechanisms, and grassroots networks for up-taking gender agenda.

6.2 Methodology

The report heavily draws on secondary data—from published journals to policy directives to gray articles. Data emerging from the literature were content analyzed identifying key patterns and categories. Relevant policies and institutional guidelines were reviewed from a gender perspective to identify the scope of gender mandates. In addition to the secondary data, some of the primary data on gender distribution and CF status were also collected. In addition, 5 key expert interviews were conducted to understand perspectives from policymakers, women's organizations, forestry networks, and forestry and gender experts to identify dominant narratives and their implications on gender agenda in community forest governance. The emerging patterns are then qualitatively analyzed and discussed with global discourses surrounding gender approaches in forest governance.

6.3 Women as Primary Users in Subsistence Forests

The early premise of community forestry in Nepal was largely been framed with a subsistence utilitarian approach to rationalize local community's engagement. Indeed, local livelihood primarily relied on the farm–forest interface and agroforestry livelihoods. Forest-based products including food, fodder, and firewood are considered significant part of local livelihoods (Ojha et al. 2009; Vinceti et al. 2013). Forests used to be an important part of household energy sources (Malla 2000) with almost 70% dependence on firewood. People are also dependent on forests for products such as grass and fodder that support livestock-based livelihoods in the rural parts of Nepal (Pandit and Bevilacqua 2011; Paudel and Ojha 2013).

Women's social–cultural roles in rural subsistence Nepal revolved around home, agriculture fields, and forests. Thus, it is quite natural that 40 years ago when CF modalities were initiated in Nepal, rationale for women's engagement in community forestry was grounded based on social roles rural women then played in society in terms of performing their household duties (Pandey 1990; Molnar 1991). As part of performing their household duties and care roles, women performed major roles in forests spanning from collecting forest food and fruits, fuelwood, fodder, leaf compost, and bedding materials, and managing grazing. Their close association with forest space and resources made them more acquainted and relatively knowledgeable about forest conditions and their resources. If tapped, women's forest-based knowledge and experiences are deemed valuable for sustainable forest management.

This recognition was followed through legal precedents. Women were recognized as "primary user" of forests in the Forest Law 1993. This recognition provided a very explicit legal precedent for women as one of the social actors to be identified and consulted in community forestry. Several explicit affirmative mandates were included in the policy frameworks and aligned through institutional mechanisms. The early years of gender agenda in practice were focused on the representation of females in decision-making spaces of CF, forming women-only institutions, and increasing women's leadership and voices in decisions. These mandates included affirmative criteria for securing women's representation in decision-making and benefit-sharing mechanisms. For instance, Community Forestry Development Guidelines (DoF 2009) place mandatory provisions to include at least 50% women in the executive committee with either chairperson or secretary being a woman. There is a provision to use 35% of community forestry user group budgets in activities that benefit women, poor, and socially excluded groups. Enabling institutional environments were created within the state forest agencies through assigning gender focal points to develop gender strategy of the Ministry of Forests and environment to increasing capacities of gender focal points and other forestry staff. In parallel to the state's forest agencies efforts, community networks such as The Federation of Community Forestry Users Nepal (FECOFUN) and The Himalayan Grassroots Women's Natural Resource Management Association (HIMAWANTI) conducted community campaigns and training programs to increase sensitivity and space for women's leadership within communities. The collective efforts of community networks and state agencies have established gender as a clear agenda in community forestry.

6.3.1 Critical Mass of Women in Community Forestry

The early years of gender agenda in practice were focused on the representation of females in community forestry user groups, forming women-only institutions, and increasing women's leadership and voices in the decision-making spaces of forest governance. Women-only community forest user groups were also formed as safe spaces for women to engage in the new modalities of community forestry. Subsequent efforts were placed to ensure gender-inclusive legal provisions, including women-friendly extension mechanisms, improving local women's leadership capacities, and reducing women's work burdens. Later, as the issue of community heterogeneity and elite capture became apparent (Buchy and Subba 2003; Pandit and Bevilacqua 2011), gender agenda was coupled with intersectional equity agenda. Subsequent efforts were then placed to include representation of women, poor, "Dalits" (so called "low caste"), and ethnic local communities in forest governance and decisions.

Currently, women hold a critical mass of 42% (87724) of membership spread over 22,645 executive committees and 204,750 executive committee members that represent community forest user groups.[3] The critical mass of women in decision-making spaces makes them visible and grants them legal rights to influence decisions in CF governance. Indeed, CF has provided an opportunity for Nepalese women to explore, experience, and engage their presence and role in the public sphere that was previously inaccessible and denied for them (Giri and Darnhofer 2010). Many of the women and men leaders engaged in community forest user groups contested and won 2017 elections (RRI 2018), which can also be attributed to prior leadership and public space exposure gained through CF. Community networks such as FECOFUN and HIMAWANTI have established themselves as critical players in advocating for gender and community rights in community forestry. An informal network—called as Female Foresters' Network[4]—has also been formed and remains actively engaged to further women's voices and perspectives in the forestry sector, including the community forestry sector. These groups run awareness and advocacy events to highlight the ways informal power relations hamper gender mainstreaming in practice, and demand improved actions from forestry actors.

6.3.2 Impacts on Forest Management and Gender Equality

Women's engagement in community forestry is associated with improved forest management. Studies confirm a positive relationship between gender distribution in executive committees with better decisions on sustainable firewood extraction, regeneration, transparent fund management, and compliance regulations, which are linked to improved environmental and governance outcomes (Agarwal 2010; Leone 2019). In addition to equitable governance, community forestry has also contributed to local livelihoods and supplemented communities' income through the use of forest resources (Thoms 2008; Adhikari et al. 2014). In some cases, CF's forest funds at the community level have been used to address the wider needs of women and other marginalized communities. For instance, soft loans and scholarships are

[3] Primary (unpublished) data collected from Ministry of Forests and Environment, December 2020.

[4] https://www.recoftc.org/stories/promoting-gender-equality-through-leadership-southeast-asia

targeted to low-income groups; healthcare facilities and aids are provided to pregnant women; and water harvesting technologies are placed in ease of issues of water insecurity.

The positive outcomes in numbers and access to resources, however, remain limited to ensure meaningful participation of women in CF. Usually, the major control of decision-making is retained by men. At present, the major share (94%) of key decision-making posts such as chairperson is retained by men, compared with 6% by women,[5] signaling that men are occupying the most powerful position of decision-making across community forest user groups. Even when women are represented in executive committees and have legal decision-making rights, women leaders across CF have experienced deep-seated resistance to exercise their rights since local gendered norms and ideologies privilege only men as leaders (Wagle et al. 2017). Many of the constraints women now face in community forestry have more to do with informal institutions and rulemaking that favor social and structural status quo in favor of men (Khadka et al. 2014; Wagle et al. 2017; Bhattarai 2020). These studies indicate that even when formal institutions and policy mechanisms ensure explicit inclusion of women in decision-making committee, benefit-sharing criteria, and engage them in policy discussions, the informal rules and norms are overbearing and continue to act as barriers for women's increased access to and control over forest management decisions.

6.4 Women as Irrelevant Actors in Commercial Transitions of Community Forests

The total area of forest land in Nepal increased from 39.6 to 44.74% in the last two decades (DFRS 2015). With an increase in the total area of forested land, Nepal's forestry sector has huge potential for the commercial management of forest resources from sustainable logging and harvesting of products, mainly in community-managed forests, in addition to creating jobs and income. The resources (i.e., wood in particular) within CF are matured across community forestry which hold potential to generate revenue (Paudel et al. 2014) that can be a good resource for both communities' livelihoods and the country's economy. Government policies and strategies have noted the opportunity to use forests to provide livelihood opportunities through sustainable management of forests. The Forest Sector Strategy 2016–2025 for example (GoN 2016) envisions a sustainably managed forest, inclusive of livelihood opportunities. A newly emerged discourse is "forests for prosperity" which has necessitated discussions on how community forestry can move beyond subsistence models toward commercial, production models of management. However, what management modalities will govern such shifts is heavily debated in Nepal with discourses around the framing of scientific, technical expertise, economic rate of returns, mechanisms of power-sharing between communities and state

[5] Primary data retrieved from MOFE, December 2020.

agencies, and practical challenges of governing the operations of scientific forest management in practice. The debate currently remains unresolved.

6.4.1 Economics Prosperity Overriding Social Equity Agenda

Gender topics and agendas are completely missing in these discussions. The majority of actors tend to perceive that gender and social inclusion topics are "unnecessary and irrelevant now" since the major objective of CF is now discussed around generating profits and ensuring economic security. Not only such a dominant narrative is prevalent, but it is also widely accepted and commonly popular. KEI respondents indicated the prevalence of a commonly dominant narrative such as "this is time to talk about prosperity, the enterprise needs to make a profit, there is no need to talk about gender and social issues" among actors from forest bureaucracy and community networks. These actors tend to emphasize that the focus is to be kept on ways of generating profits and ensuring economic security. Such discussions are mostly concentrated within community forests that have high-income potential, mostly dominated by men with topics focusing on markets, profit, and productions, with limited participation of women. There is no discussion around the differential effects of commercial management on community forests that are small-sized and have less stock of mature timber. Community forests that are small in size and have less amount of mature timber stock are likely to face differential implications of commercial trade. Global studies indicate that commercial market mechanisms create opportunities for high-capacity firms at the cost of marginalizing local and small-scale timber loggers, producers, smallholder communities, and informal forestry enterprises (Setyowati and McDermott 2016; Carodenuto and Cerutti 2014). If we consider this scenario, it is likely that small, less-value CFs, and women-only community forests[6] that manage small-sized forests with less valuable timber will not be benefitted as the mixed community forests with high-value timber unless equity and safeguard standards are placed within the economic discussions. Other equity issues such as equitable benefit-sharing mechanisms, pay standards, labor laws, and safe workplace also remain missing.

These narratives indicate the shifts from previously practiced subsistence-based community forestry to the commercial one. Given the rich mature stock, it is not uncommon among forestry actors to privilege economic gains. What is surprising though is that forestry actors tend to position two objectives of economic prosperity and gender and social equity as mutually exclusive, which does not have to be true. The existing evidence demonstrates that women's engagement is beneficial for forest sustainability (Agarwal 2010). Yet, the narrow positioning of gender and social equity as an obstacle to economic prosperity by forestry actors can be an indication of their limited knowledge of gender and social issues. Or it could also refer to

[6] Women-led community forest user groups are usually small in size, have degraded condition, and do not have valuable wood species.

forestry actors' lack of adoption and internalization of gender and equity learnings made through the four decades of experience.

6.4.2 Changing Gendered Roles and Subsistence Needs

Despite being recognized as primary users for 40 years, women's knowledge, role, and contribution are not acknowledged in the discussions surrounding commercial transitions. Ironically, forestry actors even question the need for women's engagement in the commercial management of forests. One the KEI respondent said:

> "They (forestry actors) say that "women now do not go to forests, they use Liquefied Petroleum Gas (LPG) for cooking; why are they needed to be in these (commercial CF) discussions?" They seem to justify women's roles only if it is related to household work."

At the outset, this example suggests that forestry actors are failing to see women's role in newly emerging (commercial models of) forest management because gender roles and women's needs related to forests have now changed. With the ease of transportation and increased incomes, women, for example, in peri-urban and urban areas use alternative fuel for cooking. Many women no longer use firewood as the cooking source, so they do not have to go to forests as they used to go before. So, they do not perform one of the previously performed gender roles associated with forests—going to the forest and picking firewood. Yet, in rural areas and forest-dependent communities, women still use forests for livelihood and household roles. So, this argument does not hold much merit. Yet, such discourses are taking place, and forestry actors are using such arguments as a basis to disqualify women's engagement in commercial transitions.

Forestry actors also fail to recognize the economic cost (labor, knowledge, and skillset) women bore in conserving and sustaining community forestry resources even though farm and forestry operations are maintained through women's unpaid labor in CF, due to the huge male outmigration. Women are usually the main actors who provided their care, labor, and inputs to protect and grow forest resources and have ensured forest growth and CF sustainability. Forestry actors recognize women's roles and leadership but they associate it as a "care" role—"role that women did for their household or community." They do not identify it as an economic role. They also do not foresee women as economic actors capable of playing economic roles in the commercial management of forests.

These patterns need to be understood in depth. The narratives exhibited by forest actors can be the manifestation of underlying gender frames with which they associate and accept women's engagement in forests. This discourse is potentially occurring because the majority of CF actors, including that of civil societies, possibly rationalize (and approve) women's engagement in CF as an extension of women's traditional care roles and household duties that were in perfect sync with socially ascribed gendered roles in subsistence-oriented community forestry. Socially prescribed gendered roles associated with cooking and maintaining their family's forest needs through community forestry were thus considered useful and relevant. Women were thus identified as primary users. Now, with the focus placed on commercial models, it seems difficult for forestry actors to envision women in non-traditional gendered roles, such as forest business owners and entrepreneurs. As such, women's engagement is not perceived necessary and relevant in the economic transitioning.

6.5 Institutional Environment and Adoption of Gender Agenda

There are, however, existing policy provisions that mandate the elimination of discrimination, securing 50% women in decision-making authority, and regulate inclusive benefit-sharing mechanisms—specifically the National Forest Policy, 2019—policy number 8.8. Social safeguards, inclusion, and governance—Policy and the Forest Act 2019, Section 22. These policy directives are yet to be linked with the commercial transitions.

The continuation of these discourses despite the legal mandates to engage women in economic transitions indicates persisting gaps between policy aspirations and their adoption by forestry actors. It also refers to the limited institutionalization and internalization of gender principles and values by and within CF actors and institutions. Or else, one could expect to have witnessed the incorporation of some compliance and safeguarding mechanisms on topics of gender equity in the emerging commercial models of CF.

Key experts indicated that this is due to limited understanding of forestry actors on gender issues wherein gender is largely seen as an issue of diversity and representation only—mostly achieved through metrics of women's share in decision-making posts. There is also an overwhelming tendency within forestry actors to highlight gender results at the community level only and not within their institutional structure and practices. This creates a situation of ambivalence for gender agenda wherein gender results at community levels are targeted but with limited sensitivity and adoption of these agendas by the performing institutions themselves. As such, there is very limited reflection and internalization among forestry actors on gendered norms and biases prevalent within the institutional environment. At times, forestry actors themselves—in particular—forest bureaucracies and universities institutionalize masculine spaces which create an uneven playing field for women and negatively affect gender-inclusive policy and practice (Christie and Giri 2011; Wagle et al. 2020).

Key experts also indicated a sense of gate-keeping prevalent around advancing the gender approach within the community forestry program overall. Community forestry's gender policy and explicit mandates on representation, benefit-sharing mechanisms are unique and innovative. However, these are portrayed overly positively in ways that limit further critical exploration and gatekeeps the progress. Some key respondents said:

> "Everyone feels proud about community forestry. They boast that we (Nepal's community forest) are the best in terms of gender mainstreaming. This "being in the best" sometimes is used so positively that it masks the gaps that are out there (within the institution). At times, it comes across like this: we are good (compared to others) and so it is okay if we do not do much around it (anymore). It does not help to expand the gender agenda."
>
> "The increase in representation of women leaders in decision-making positions is also portrayed as overly positive. Attention is not paid to analyze the barriers and challenges that women, ethnic groups continue to face in CF and how to address those."

Though CF is highlighted as one of the model programs in terms of gender equality and social inclusion, the internalization and adoption of gender equality values remain fairly low across forestry actors and institutions. Women's representation and engagement are very minimal in other collective management modalities. KEI also indicated that gender approaches and work are largely treated as "project work" with relevance only at the community level (i.e., for community women) and remain isolated from the operational culture and accountability of forestry institutions. There is limited preparedness on forestry actors to come up with gender-responsive solutions that can map the gender gaps and relationships. Another key respondent said:

> "In a local workshop, a local community forestry woman asked us (policy makers) this question. She said, "I want to open my own forestry business using a forest product. But, I do not have the capital to open such a business. I do not own land, so I cannot even use it mortgage and get the capital. Will the forestry sector provide (help facilitate) me some loans so I can be a part of this economic growth from the forests that I and many other women protected for so many years?" We are not even thinking and discussing those topics, let alone be prepared to come with inclusive measures to fill those gaps."

6.6 Rethinking Gender Constructions in Community Forests

Nepal's 40 years of gender agenda and practice provide interesting yet conflicting lessons. On the one hand, community forestry's progressive legal and institutional mandates on gender agenda have recognized women's role and ensured their representation in decision-making spaces. Such legal and institutional mechanisms have given a positive edge to develop a critical mass of women's leadership and decision-making in public spheres. As such, Nepal's community forestry modality is widely touted as a global model for gender mainstreaming for collaborative forest management. On the other hand, the shift to the commercial orientation of community forestry with a focus on the scale of production and market is perceived to alter long-standing gains made in gender equality and social inclusion. The discourses and gender agenda that surfaced during the commercial transitions are counterproductive to the long gains made for gender agenda and pose risks to advance gender equality in community forestry.

The ongoing discourse surrounding commercial transitions of community forests exhibits problematic gender frames around women's roles and engagement in forests. Women's role, engagement, and leadership in community forestry are largely construed and justified as an extension of their care roles in a then subsistence economy context of Nepal. These constructions of women's care roles have not changed much despite women's critical mass and leadership in community forestry. Using such constructions pigeonhole women's leadership and further compromise their prospects to engage as economic actors in the commercial transitions of forest management. Such narrow framing and problematic constructions are likely to create risk where women's economic roles in forestry is not recognized, and yet they will continue to bear the costs of conservation without receiving fair recognition and benefits. Such exclusion can create negative implications for women's rights and their chances to improve their livelihood and empowerment through commercial models.

These discourses also question the limits of policy provisions and the approaches of gender mainstreaming currently practiced in community forestry. CF's progressive policy mandates on gender diversity and inclusive benefit sharing have given a positive edge to develop a critical mass of women's leadership and reap fair livelihood benefits. Yet, these interventions remain limited to adequately identify and address the risks surfacing from deep-seated gendered norms, constructions, and male privilege embedded in the wider social and economic systems of Nepal. Limited understanding of gender concepts amidst forestry actors and lack of institutional safeguards and accountability are not conducive to addressing the foreseeable gender gaps in commercial transitions. The challenges for ensuring gender equality agenda in community forestry are thus twofold: First, gender approaches should be able to adequately respond to the differentiated needs and rights of women, ethnic groups, and other marginalized actors engaged in forest policy, institutions, and governance mechanisms. Taking such an approach will help to expand the current gender agenda from representation and benefits to adopting gender-responsive extension and outreach programs that are better equipped to address gender gaps and unequal relationships. Second, the forestry sector needs to consciously coordinate and increase the forest sectors' interface with non-forestry actors and institutions to create collective channels for transforming structural inequities that perpetuate gender inequality and social exclusion.

There is an urgent need to correct the misconstrued discourse by linking women's role and economic contribution to maintaining sustainable forest conditions and stocks. Women can also be envisioned in new roles such as that of forest entrepreneurs and business operators. Some existing policy provisions mandate the elimination of discrimination, securing 50% women in decision-making authority, and regulating inclusive benefit-sharing mechanisms. It would be useful to link existing policy provisions with the commercial transitions discussions so the gender agenda remains intact in these discussions. Forest policy and extension approaches need to move beyond representation and benefits sharing to addressing gender gaps and barriers that women and marginalized groups face to take part and ensure their voices to shape these transitions. Forest extension approaches and interventions should be deliberately designed in ways that help women to increase their access to land, capital, and markets and fully engage as social actors. The benefit-sharing modalities within different sub-groups of communities should also be discussed.

Besides timber, commercialization of other forest products such as NTFPs, herbs and forest foods, and eco-cultural tourism needs to be explored which could provide direct avenues for women and indigenous communities to engage and benefit from the commercial transitioning of CF. Moving forward, there is a need for a reframed approach that moves beyond the gender construction of women's care work tied to their gender roles in a subsistence context of forests to the one that sees and prepares women, ethnic groups in new roles as economic actors in the commercial forest modalities and its supply chain.

Moving forward, the following actions are suggested as priority interventions:

- **Redefine the Economic Growth-Centric Slogan of "Forestry for Prosperity" and Elaborate on It to Accommodate Gender Equity and Environmental Dimensions**. The gender strategy within the forestry sector calls for a revised framing from its existing notion that rationalizes women's engagement in community forestry as an extension of their gendered care roles to the one that foresees and prepares women, ethnic groups in new roles from caretakers of forests to stewards and entrepreneurs. There must be a sustained and increased investment in retaining gender and equity agenda in these new discussions, with leadership and safeguard provisions in place for women and social groups to engage and benefit from community forestry. In so doing, gains achieved from community forestry in terms of the participatory process, women's increased representation, and access to resources and opportunities need to be retained through enforcing policy and institutional safeguards. In particular, the revenue/income of community forests should be managed in ways that address the constraints and meet the aspirations of women, ethnic groups, and other socially marginalized groups. Also, the forest sector needs to prepare its extension and advisory services to tackle women's lack of access to land and other economic resources which can hinder their opportunity to engage as economic actors.
- **Design Forest Policy, Extension, and Advisory Services to Tackle Structural Barriers Faced by Women and Other Marginalized Groups:**
  Forest policy and extension should be responsive to meet the differentiated needs of different sub-groups of women and men while paying attention to structural factors that perpetuate gender inequality and social exclusion. The gender and social inclusion strategy should be expanded to include an intersectional approach to identify the most excluded groups of men and women across intersecting categories, as well as the drivers of exclusion. For example, providing child care support to mothers can increase women's access to forest training and opportunities. Community forestry actors need to take proactive measures to tackle deep-seated behaviors, biases, and prejudices among forestry actors and institutions that perpetuate gender inequality. There is an urgent need for conversations, capacity enhancement, and behavioral change programs to confront such gendered mindsets of forestry actors and promote learning and change, across forestry policymakers, local communities, civil societies, and international development communities. Such efforts should be complemented with mass communication campaigns that showcase women in non-traditional roles including as leaders, and economic entrepreneurs.

- **Mobilize Women's Critical Mass of Leaders to Advance Political Empowerment of Women and Other Marginalized Groups:**
  The critical presence of women leaders across community forestry is an opportunity to develop more gender-inclusive and environmentally friendly local development plans and targeted investments to address structural inequities. However, the administrative and other governance functions are still operating with centralized mindsets. Women leaders in community forests face a lack of cooperation from elected men representatives and their tendency to control major budgets and decision-making mechanisms. There is a need to create an enabling environment for women's leadership through men's allies and engagement.

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Diversity of Forest Genes: Impacts on the Structure and Function of Soil Ecosystems Under Changing Climate

7

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Abstract

Forests provide a critical habitat for different species and in turn support different ecosystem services for Earth's functioning. With climate change, a risk to the food system, with its function of capturing and storing carbon, the importance of forest biological diversity (gene pool) becomes more pivotal. However, the biological diversity at different levels of the inhabiting species determines their ability to respond to possible climate change.

The species' genetic diversity critically affects its relation to other species through different structural and functional components in the associated soil ecosystem. As a consequence of the association of the genes, important processes such as energy flow, biogeochemical cycles, and signaling secondary metabolites are altered. Understanding such associations is a prerequisite, as it can impact diverse ecosystem services/productivity of forests such as food and fiber. Apropos, the present chapter highlights different components of the forest ecosystem, their interplay, and their impact on soil structure and function, thus affecting different ecosystem productivity.

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Keywords

Forest ecosystem · Genetic diversity · Soil structure · Soil function · Soil ecosystem

7.1 Introduction

Forests are critical habitats for Earth's terrestrial and aquatic biodiversity. With an unequal distribution and coverage of 31% of the global land area (FAO 2020a), the forest contains over 80% of terrestrial biodiversity. These forests, as ecosystems, vary widely throughout the world and include the following general categories (FAO 2020b), viz. (1) boreal forests dominated by woody species, (2) temperate mixed forests with several mixed broad-leaved species, (3) temperate evergreen forests with a variety of coniferous species, (4) tropical rain forests of great diversity, (5) tropical deciduous forests with relatively low diversity, and (6) tropical dry forests with few species growing in open stands. Notably, the tropical rain forests and boreal coniferous forests are the least fragmented, while subtropical dry forests and temperate oceanic forests are the most fragmented. Within these types of forests, the biodiversity varies with geography, climatic conditions, soil type, and vegetation. The forest vegetation type or the diverse plants on the forest floor provide a species-specific impact on soil properties and microbial communities through the difference in litter dynamics and root exudates, thereby influencing the composition and function of the soil. Therefore, for maintenance of the soil health along with its biotic components, the genetic diversity of forest vegetation, especially trees, is primarily important as it is critical to the health of forest trees because of their limited mobility, slow reproductive maturity, and multiple encounters with the changing environment during the whole lifespan. The genetic diversity in the trees provides an adaptive benefit and resilience to various biotic and abiotic stress conditions.

The forest soil is generally the main component of the forest ecosystem and is characterized by the plant roots, litter layers (O horizon), nutrients, organic matter, and soil animals (Weston and Whittaker 2004). The forest soil functions as a (1) support for water and nutrient supply to forest vegetation, (2) reservoir of stored carbon, thereby regulating the atmospheric carbon dioxide, (3) watershed and hydrological functions for streams and rivers, and (4) a habitat for numerous microorganisms, representing the biomass (Boyle and Powers 2013). The forest soil structure along with its nutrient pool is a major component that influences microbial community structure. These microbial communities, in turn, act as regional drivers for the aboveground diversity of the flora and fauna and other soil ecosystem services.

Although the forests are self-organizing systems with numerous natural processes that counter to internal and external drivers, climate regulation, biomass production, water supply, and purification, pollination, and the provision of habitat for forest species are all critically important ecosystem services provided by forests (Bauhus et al. 2010; Brockerhoff et al. 2013; Decocq et al. 2016; Mori et al. 2017). Deforestation and forest degradation remain the main threats to the forest ecosystem [the global forest area decreased by 178 million ha between 1990 and 2020 (FAO 2020b)]. The need for agricultural expansion is the main driver for forest deforestation. For example, large-scale commercial agriculture (mainly livestock and soya bean and oil palm cultivation) contained 40% of tropical deforestation between 2000 and 2010 (FAO 2020b). This has not only reduced the coverage of forests, but also the biological diversity they harbor. With climate change, a major risk to the food system, the importance of forests, and forests' biological diversity (gene pool) have become pivotal to the survival of mankind.

7.2 Forest Biological Diversity

Biological diversity encompasses the number, variety, and arrangement of living organisms. It is quantified into three levels, viz. (1) heritable genetic variation within and between populations of a given species, (2) variation among species in terms of number, abundance or scarcity, and endemicity of species, and (3) variation among ecosystems and how species interact with each other and with their environment.[2] In general, there are four foremost aims of assessing the biological diversity (Bachmann et al. 1999): (1) for a scientific understanding of the structure, function, and evolution of the ecosystem, which is necessary as a basis for the management of resources for its survival and productivity functions, (2) for the conservation and development of genetic material for the selection and genetic improvement of individual species for planted forests and agroforestry, and (3) to monitor the impact of land management interventions and natural and anthropogenic environmental changes on biological diversity.

In the forest ecosystem, biological diversity encompasses all life forms found within forested areas and the ecological roles they perform. It not only contains trees, but different animals, microorganisms, and associated genetic diversity are also a part of it. The forest's biological diversity can be structured into different components, viz. ecosystem, landscape, and population genetics, and their interactions, to adapt to a continually changing climate. With the complex interplay among and within different components in the forest ecosystem, the Conference of the Parties recognizes "Forest biological diversity results from evolutionary processes over thousands and even millions of years, which, in themselves, are driven by ecological forces such as climate, fire, competition, and disturbance. Furthermore, the diversity of forest ecosystems (in both physical and biological features) results in high levels of adaptation, a feature of forest ecosystems that is an integral component of their biological diversity. Moreover, within specific forest ecosystems,

Table 7.1 Forest biological diversity uses

S. no.	Support	Description
1	Livelihood support	• Support 86 million green jobs. • Fuelwood for 880 million people worldwide.
2	Ecosystem services: home to pollinators (benefit from animal pollination for fruit, vegetable, or seed production.)	• Effect 75% of the world's leading food crops. • Effect 35% of global food production.
4	Nutritional resource	• Source of wild edible fruits, wild meat, edible insects, edible plants and products, mushrooms, and fish. • 100 million people in the European Union (EU) regularly consume wild food • 2.4 billion people—in both urban and rural settings—use wood-based energy for cooking.
5	Human health	• 28,000 medicinal plant species are currently recorded as being of medicinal use and many of them are found in forest ecosystems.

FAO and UNEP (2020)

the maintenance of ecological processes is dependent upon the maintenance of their biological diversity".[1]

Although it is not very easy to quantify the value of forest biological diversity, for future survival it becomes empirical to obtain relative values of these to establish conservation areas and programs, and future breeding programs. Consequently, Flint (1991) has developed a typology of biodiversity values, including the use and non-use values. The use-value is subdivided into direct, indirect, and optional values. Among the direct values, (1) the consumption of forest and tree products such as meat, fruits, fodder, medicines, and wood; (2) improving production through the use of genes in tree improvement; and (3) uses of ecosystems for recreational, tourist, cultural, and religious purposes are included. The indirect value refers to nutrient cycles, soil conservation, and water resource management. The option value usually refers to the creation of conservation areas and parks or reserve areas based on the spiritual value (Table 7.1).

Relationships between forest type, biodiversity, and ecosystem services are highly interconnected. The linkage between forest biological diversity and ecosystem services enables a forest to respond to disturbances, as the forest biodiversity imparts resilience to the forest against external disturbances such as climate change and ecosystem processes maintenance. Resilience, in general, is facilitated by forest and tree diversity, leading to a reduction or dilution of resources (e.g., for herbivores), diversion or disruption, and multi-trophic interactions (e.g., enhanced

[1] https://www.cbd.int/forest

abundance and action of natural enemies) (Jactel et al. 2017). The presence of a greater number of species increases the probability that an ecosystem will contain a species that grows faster, is more resistant to a particular disturbance, or has another beneficial trait that leads to better ecosystem functioning or the provision of services, in comparison with communities. Studies have established that an assembly of genetically diverse organisms is more resistant to pathogenicity than monoclonal populations (Zhu et al. 2000; Burdon 2001). On the other hand, with fewer species (Lefcheck et al. 2015), declining biodiversity is likely to reduce the resistance of forests to climatic extremes (Isbell et al. 2015) and pests, pathogens, invasive species, and other stressors (Jactel et al. 2017) and reduce the supply of ecosystem services in general (Vilà and Hulme 2017). Although the forest species are vital to the functioning, not all species are essential in the same way in maintaining the ecosystem processes. The species which are very crucial for the maintenance of the ecosystem services are usually assembled into functional groups, containing species performing the same functional roles, for instance, pollination. This functional diversity concerning ecosystem properties imparts comprehensive stability to forest resilience.

Furthermore, there are interactions between different ecosystem services as well, depending on the combination of trees and the type of stand involved. Some mixes of trees are better for providing certain services, but other mixes of trees or even single-species forests are more effective for other services (van der Plas 2019).

7.3 Forest Genetic Resources

Genetic resources from forests are innate materials of the forest trees and other woody plant species (shrubs, palms, and bamboo) that are of actual or potential economic, environmental, scientific, or societal value. The molecular genetic diversity within the forest community or species or population represents manifestations of biological diversity at a distinct scale. The basis of all expressions of biological diversity is the genotypic variation (genetic diversity) found in resident populations of a forest. The additive genetic variance accumulated over time within a species at the population level governs an array of essential ecological and physiological tolerances to the natural selection or response to environmental changes (adaptive capacity). This is achieved via regulation of interactions among inter-specific competitor species, along with suitable mechanisms of the dispersion, that comprise the essential determining factor of a species' potential to retort toward adaptation or survival (Pease et al. 1989; Halpin 1997).

The genetically diverse presence among forest trees is higher than other organisms sharing the same habitat (Hamrick and Godt 1990). Such diverse populations of trees offer a stable foundation to different biodiverse organisms. The genetic diversity in the forest trees complements the species diversity, especially for the functional group of pollinators (insects, bats, and birds) and organisms that aid in seed dispersion (birds, mammals, etc.) (Thompson et al. 2009). Among forest ecosystems, the genetic variation among forest tree populations exhibits diversity in characters such as growth rates, productivity, secondary chemistry, and physiological processes (i.e., photosynthesis and water use/loss). These characters may affect directly or indirectly the growth and development of other species in the same habitat through allelopathy effect, competition, herbivores, their predators on plants, and other processes (Bossdorf et al. 2009; Hughes et al. 2009; Clark 2010), creating unique communities. Nevertheless, these community interactions can extend to affecting ecosystem processes associated with individual genotypes (Schweitzer et al. 2005; Madritch et al. 2009). The variation in population genetic diversity or genotype composition not only affects the fitness of individual trees or other organisms but also can have far-reaching effects up to the level of ecosystem properties. For instance, plant genotypic diversity and genotype identity have been shown to affect biomass production and community invisibility and also the invertebrate diversity of the higher trophic levels (Crutsinger et al. 2006; Vellend et al. 2010).

Plant genotypes can vary considerably in the quantity and quality of leaf litter they produce, creating genotype-specific differences in litter dynamics and nutrient release if co-occurring genotypes in a litter mixture interact in ways similar to co-occurring plant species. This nutrient concentration difference among genotypes can vary up to 50% in the decomposition rates, like as observed in golden rod species (*Solidago altissima*), where the decomposition rate was more than twice that of genetic variation (Crutsinger et al. 2006). Studies have also revealed a difference in litter decomposition and nutrient release among different Populus genotypes, suggesting genotypic selection might lead to adverse effects on the ecosystem of restored forests such as the condition of their associated soils, via litter inputs, pools of nitrogen, and rates of net N mineralization (Schweitzer et al. 2008, 2012; Madritch et al. 2009). In the studies, the genetic diversity was also found to be correlated to soil microbial community composition, microbial exoenzyme activity of a carbon-acquiring enzyme, and availability of soil nitrogen. It was empirically found that soil microbial community composition changed as gene diversity changed and that the activity of β-1,4-glucosidase and the availabilities of ammonia, nitrite, and total inorganic nitrogen in soil were highest at moderate levels of genetic diversity.

Diversity in Secondary Metabolites: Plant secondary metabolites have an important role in many of the ecological processes that shape biodiversity. Coniferous trees, including pine and other gymnosperms-dominated forests of the mountainous regions, have a significant variation in the composition and diversity of the monoterpenes among species, genotypic, within populations, and environmental conditions. These monoterpenes have a wide range of properties, including antifungal and anti-bacterial properties, and mediate the interaction between vertebrates, insects, invertebrates, and other plant species, thus shaping the ecosystem composition. Studies have found that the chemical diversity of monoterpenes of individual trees of Scots pine (*Pinus sylvestris*) is significantly positively associated with the species richness of the ground vegetation beneath each tree, which is mainly the result of an effect among the non-woody vascular plants (Iason et al. 2005). The needle litter from Scot pine trees contains only 36% fewer monoterpenes than living green needles, and of this amount, 32% remains in needle litter after 7.7 months (Kainulainen and Holopainen 2002). They may reinforce and alter the local soil ecosystem, as they can lead to locally variable inhibition of decomposition and nitrogen mineralization by the soil microbiota in pine ecosystems (Paavolainen et al. 1998). Also, these monoterpenes can directly affect other plant species, producing allelopathic effects that inhibit germination, seedling growth, and survival (Linhart and Thompson 1999; Romagni et al. 2000).

7.4 Soil Ecosystem: Structure and Function

The soil is a complex and dynamic system that represents a habitat for a wide range of diversity (the most species-rich ecosystem on Earth), and therefore supports different ecosystem services (Selck et al. 2017; Silvertown 2015). In the terrestrial ecosystems, soils are the primary regulatory components, with their regulation on diverse geochemical and ecological functions (Wall et al. 2010; Crawford et al. 2005). These soils in distinct natural ecosystems are regulated chiefly by abiotic factors (pH, organic matter, etc.), which form the primary structure and composition of soil microbiota, thereby affecting soil structure and function (Fierer 2017; Kivlin et al. 2014). Typically, four key functional roles are required for the maintenance of soil health, defined by blending separate biological developments such as transformations of carbon products, cycling of essential nutrients, conservation of soil composition, and regulation of other bio-populations.

The biodiversity of organisms present in the soil is the chief transformer that determines the essential functioning of soil ecosystem services (Silvertown 2015). The soil biodiversity is majorly constituted by microbiota such as bacteria, fungi, and micro- and macro-fauna, and flora, with each level having a designated position in the ecosystem's configuration and function. These organisms can be classified on the functions, viz. (1) chemo-engineers; (2) bioregulators; and (3) eco-engineers (Turbe et al. 2010). Chemo-engineers are microorganisms such as decomposers and transformers that actively cycle essential nutrients such as carbon, nitrogen, phosphorous, and other micro-compounds. Bioregulators regulate the changing aspects of populations, such as pests and diseases, and, as a result, enhance the flexibility and stability of soil ecosystems. Ecoengineers are responsible for soil structure and maintain the structure of the soil by promoting networks of pores and the expansion of complex biostructures, which overall enhances aggregate stability.

The hyper-diverse soil communities belowground and aboveground create a multitude of dynamic micro-environments for various ecosystem services. Nevertheless, alterations in the profusion of species diversity—notably those species which affect water and nutrient subtleties, trophic exchanges, alter the composition and performance of ecosystems (Liu et al. 2008). Therefore, soil biodiversity imparts a beneficial effect on the soil for resilience against the varied disturbing impacts of changing climate in different ecosystems. The ecosystem amenities are highly dependent upon soil biodiversity, together with trophic and behavioral interactions, sequentially and spatially. Soil ecosystem services differ on the soil ecosystem, i.e., composition and functions (biotic and abiotic elements and all underlying inter- and intraspecific interactions among them) and other natural activities occurring in soil (Morgado et al. 2018). The formation of the soil ecosystem is accountable for all adaptations among organisms. However, the role and function of organisms in the soil also alter the structure of the ecosystem.

The evaluation of biodiversity in different ecosystems along with species-level differentiation is thus required on account of the multiple sources of variations. Such variations may include sequential changes acquired in the long run and short-term seasonal variations in number, species richness, and/or rarity through different phases of the organism's life cycle; migration of animals in and out from ecosystems; their phase in community advancement; physical position within the ecosystem from the soil to the crown of individual trees; and geographic scale (global, regional, national, ecosystem, habitat, or patch). However, knowledge about how species' relationships and structure influence soil functioning is essential for long-term soil monitoring and management (Van Straalen 2002).

7.5 Forest Biodiversity and Soil Structure-Function

The plant diversity is regulated by an array of processes such as herbivory, interspecific seed dispersion variations, and the distinct responses of plants to heterogeneous resources such as water, nutrients, and light. The plant diversity in the forest ecosystem results in variations in the soil ecosystem productivity, sustainability, and stability at various scales. These diverse plant species have certain effects on controlling the surface runoff, soil erosion, erosion of nutrients, and improvement of soil moisture content through increased leaf area index (Lange et al. 2014) and in carbon sequestration (Van der Plas 2019). Additionally, several studies have shown that the total organic matter and total and available nitrogen present in the soil are related to the α-diversity index of plants (Liu et al. 2008), testifying that the change in species might elucidate the discrepancy between soil characteristics and the underlying trigger–effect relations in them. Specifically, the water-related interactions include differences in rainfall interception by the canopy, transpiration, water infiltration or storage in the O horizon, and hydraulic redistribution. The plant diversity also responds differentially to compensatory responses to resources. For instance, at nitrogen-limited sites, tree species that are nitrogen fixers are likely to improve the functional group in mixed stands.

Organic carbon present in the soil greatly influences various soil processes and functions and is a major resource involved in ecosystem functions, apart from direct benefits to mankind (securing food production) (Wiesmeier et al. 2019). Increased organic carbon in the soil also affects other functions of the ecosystem and their services include the stores of nutrients, elevated water-holding capacity, soil aggregation, and retention of pollutants (Lal 2004; Kibblewhite et al. 2008; Guo et al. 2019). The soil organic carbon actively participates in mediating global climate change. It is estimated that the global soil contains more organic carbon than both the atmosphere and other vegetation combined (Carvalhais et al. 2014). Therefore, a small change in soil organic carbon can have a great effect on the carbon cycle. For instance, the rapid changes in global land use can force the soil to be the source of atmospheric CO_2, instead of being a sink for atmospheric carbon.

The diversity of plant species might affect the formation of organic carbon and its accumulation in soil with the help of decomposition and transformation of ground plant litter. Many research studies have reported positive, neutral, and negative influences of plant species diversity on soil organic carbon (Chen and Chen 2018; Dijkstra et al. 2005; Carol Adair et al. 2018). As a primary mechanism, vegetative dissimilarity in physiology, structure, and lifespan in plant genotypes can have a varied impact on soil carbon, due to differences in the magnitude of diversity–productivity relationships (Carol Adair et al. 2018), ultimately affecting underlying species effects on nutrient cycling (Liu et al. 2008). The genetically diverse plant resources, improve plant litterfall and other root inputs to the soil, provide habitat for varied microorganisms, and thereby can increase soil organic carbon.

The carbon content of the soil is more stable because of the action of microbial action that thrives upon energy derived from organic matter decomposition. (Sayer et al. 2011; Chen and Chen 2018). The microorganisms are in abundance in the soil and display the highest level of genetic diversity along with their functional structures (Table 7.2). Diverse plant communities can facilitate high quantities and quality of plant-derived inputs to soil microbes and detritivores by using bottom-up effects (Eisenhauer et al. 2013), which has cascading effects on the abundant diversity at higher trophic levels in the soil (Scherber et al. 2010; Eisenhauer et al. 2013). With the increasing diversity of functional groups (more appropriate for ecosystem function than the richness of the species) (Reich et al. 2004), a high degree of heterogeneity of functional plant characters may improve the effect of plant mixtures on soil microbes and their induced soil organic carbon via plant litter with distinct chemical and physical traits (Wardle 2006; Liu et al. 2018). This effect of species diversity on soil carbon may change with the soil depth because of the higher microbial diversity present in the root biomass in deeper soil (Mueller et al. 2013) and with time due to increasing interspecific complementarity (Reich et al. 2012; Chen et al. 2019) of both plants and microorganisms. Specifically, microbial organisms accelerate the swap of essential nutrients between forest plants and trees, and soil. The microorganisms synthesize extracellular enzymes in the soil (soil health and quality indicator) and have a profound function in several biogeochemical reactions of organic matter decomposition, regulation of global carbon, and nutrient requirements and therefore preserve soil functionality in terrestrial ecosystems (Nannipieri et al. 2002). In general, variations in organic carbon can easily be determined by the balance between carbon output with the help of microbial decomposition of plant litter and existing organic matter present in the soil (Castellano et al. 2015; Cotrufo et al. 2015). Microorganisms not only play a vital role in carbon fixation, but also contribute to the other nutrients cycling; for instance, Mycorrhizal fungi and nitrogen-fixing bacteria provide nitrogen to approximately 5–20% of grasslands and savannas, 80% temperate and boreal forests, and up to 75% of phosphorus, uptake by plants annually (Van Der Heijden et al. 2008). The nitrogen-fixing bacteria are vital regulators of plant development since plants cannot

Table 7.2 Soil microbial flora

Class	Organisms	Role	Reference
Soil microbiota	Bacteria, archaea, and fungi	• Contribute mainly to decomposition processes • Carbon and nutrient cycling • Improve nutrient uptake (e.g., helping N fixation) and/or regulating plant hormones • Play also important symbiotic interactions • Disease defeat and plant • Plant growth regulation	Wurst et al. (2012), Jacoby et al. (2017), Redouane et al. (2021)
Soil microfauna	Nematodes, protozoa, and rotifers	• Regulate: • (1) Nutrient cycling by improving the availability of nutrients to other species (e.g., through their feces) • (2) Population size and activity of bacteria and fungi, and • (3) Dispersion of crucial rhizosphere microbiota	Wurst et al. (2012), Sarkar and Singh (2021), Li et al. (2021), Čerevková et al. (2021)
Soil mesofauna	Acari, Collembola, Tardigrada, Protura, Diplura, and Enchytraeidae.	• Mainly herbivores, bacterivores, or fungivores. • Contribute to nutrient cycling, pest and disease suppression and serve as food for other soil Organisms and participate in soil biota distribution	Wurst et al. (2012), Amasya and Narisawa (2021)
Soil macrofauna	Macroarthropods (e.g., isopods. spiders, insects) along with soft-bodied organisms (e.g., annelids, gastropods)	• Litter fractionation and predation on other soil-dwelling • Organisms often called “ecosystem engineers” • Responsible for changing the habitat structure, in terms of its physical, chemical, and structural properties. • Contributing to different soil functions	Wurst et al. (2012), da Silva et al. (2021), Coelho et al. (2021), Baranová et al. (2021), Coulis (2021)

(continued)

Table 7.2 (continued)

Class	Organisms	Role	Reference
		such as decomposition and nutrient cycling • Water infiltration (e.g., by burrowing behaviors), suppression of pests and diseases, and as predators regulating other biotas	

fix atmospheric nitrogen and nitrogen is bound together with phosphorus and potassium, the main elements that limit plant productivity.

7.6 Dependence of Microbes on Soil

Soil microbial (bacterial) communities are formed by numerous edaphic elements, comprising soil's texture and its chemistry, as well as biotic factors such as mycorrhizal activity associated with plant roots and aboveground litter, and other decomposing organic matter, and variances in rooting depth, canopy cover, and litter quality/quantity (Lladó et al. 2018). The discrete soil and vegetation properties, because of the formation of diverse microhabitats, can prompt different soil microorganism species (Bell et al. 2009; Zak et al. 2003). The soil fungal and bacterial communities, which are often dependent on soil water and resource availability, respond differentially to global warming (Classen et al. 2015).

7.6.1 Soil Temperature

The soil temperature can have significant consequences on soil microbial community structure and functioning. Studies have found that at tallgrass prairie sites (Zhang et al. 2005), soil temperature can change the microbial community structure in a mineral soil, even after 15 years of soil warming, by changing the ratio of fungi to bacteria and reducing the abundance of fungi, causing a shift toward Gram-positive bacteria and actinomycetes (Frey et al. 2008). Consequently, at higher temperatures, some microbial communities can metabolize specific substrates that are not used by microbial populations growing at lower temperatures (Bell et al. 2009). Moreover, the differences in soil temperature can change the structure of microbial communities and impact heterotrophic respiration by altering the rate of microbial uptake of soluble substrates, microbial respiration rate, and activity of extracellular enzymes (Bell et al. 2009).

7.6.2 Soil Moisture

Soil moisture is another major element that affects the microbial structure of the forest floor. Moisture levels can impact soil microbial communities and regulate microbial activity across a wide range of environments, such as biofilms, saline water, wood, food, and soils (Suseela et al. 2012). Soil moisture efficiently augments substrate fluxes to the cell surface, while low moisture can constrain microbial activity by dropping intracellular water potential and related enzymatic activities. Dry soil types harm bacteria much more than fungi (de Vries et al. 2018). Moreover, if both fungal and bacterial communities become actively proportional at a higher temperature, with no exception, the growth and sustainability of fungal groups will be favored in such dried soil. However, by physiological adaptation, some bacterial communities may overcome high-temperature effects, although the physiological adaptation of soil microbial communities has not thoroughly varied over time with increased temperatures (Romero-Olivares et al. 2017).

7.6.3 Ecological Communal Structure of Soil Microflora

In addition to edaphic factors, at a fine spatial scale, the ecological communal structure of soil microflora is also defined by two important biotic factors (Zhang et al. 2018a, b; Bahram et al. 2018), the input of litter and its predisposition by plants, and a top-down regulation by predators (Gao et al. 2019), such as bacterial, fungal, and virus species and protists. For instance, the high diversity of viruses present in abundance in soil ecosystems regulates the soil microbial and fungal communities (Johnke et al. 2014; Pratama and van Elsas 2018). Although bacteriophages and mycoviruses are extremely host-specific, they are found to likely change the bacterial and fungal population composition in microbial communities (Ghabrial et al. 2015). The regulation of microbial diversity by predators can also be understood by examples of protists that feed on typical soil bacteria that reduce the abundance of certain bacterial species from local niches, thereby altering the communal structure via specific prey selection (Bonkowski 2004). In general, toxin-secreting bacterial species such as *Pseudomonads* (gram-negative bacteria) are avoided by protists; however, these Gram-negative bacterial species are much easily digested. This preferential feeding upturns the ratio of Gram-positive to Gram-negative bacteria.

On the contrary, predation by protists and viruses means that many diverse bacterial and fungal groups also feed and/or compete with other microbial communities by producing antimicrobial agents and/or toxic compounds in the soil that lead to a typical increase in growth rates of competitors that produce such compounds (Boer et al. 2005). Many bacterial groups, for example, myxobacteria (Gram-negative soil bacteria), feed upon lysis of other bacterial groups (Petters et al. 2018), while the *Collimomas* spp. feed upon the fungal groups present in soil (Leveau and Preston 2008). Strong bacterial–fungal competition in topsoil is ubiquitous and is greatly facilitated by antibiotic-resistant genes. Indeed, a negative interaction between fungal and bacterial communities can even reduce the soil's organic matter (Fontaine et al. 2003) also. The functional changes via taxonomic alteration in microbial communities benefit terrestrial plant fauna (Geisen et al. 2018).

Competition for simple substrates that are derived from plants implies significant inferences about microbe-driven processes in the soil. However, the consequences of higher foraging stress by microbial communities and their consequent physiological adaptation can vary with time, and thus, the adaptation may lead to distinct impacts on their nutrient selection.

7.7 Interplay Within and Among Species for Ecosystem Functions

The interplay within and between different species (plants, animals, and microorganisms) and ecosystem functions within the forest are dynamic (Fig. 7.1). The different species (individually or in the group) drive a range of factors that benefit or harm the existence of other species and in turn affect the soil ecosystem and its properties. For instance, in the deciduous and sclerophyllous forest, the humus profile is usually weaker than that in the coniferous forest (Cong et al. 2015), which acts as a driver for structuring the microbial communities. Nevertheless, different soil environmental characteristics such as soil pH, area (Lauber et al. 2009; Kaiser et al. 2014), and the tree species composition impart a robust influence on microbial community structure rather than the soil environment. These abiotic and biotic factors impact soil microbial community structure and play a crucial role in predicting how microbe-mediated processes initiate ecosystem responses to global changes in the environment (Nemergut et al. 2014).

7.7.1 Plant Diversity Effect on Microbes

Changes in plant diversity are known to affect aboveground ecosystem functioning, but changes in plant diversity also have implications for the belowground ecosystem functioning, including the diversity of belowground communities of other organisms (Schmidt et al. 2002). A higher plant species/functional group assemblage abundance can nurture an increased net primary productivity rate in the environment (Tilman et al. 2001). The interactions among plants and microbial communities may in turn affect the decomposition of organic material and the mineralization of nutrients, thus controlling the ecosystem's productivity.

Soils below different tree-dominated forests possess different microbial communities and thus have a different rate of leaf litter decomposition and mineralization processes due to different plant traits, such as plant growth rate, productivity, level of secondary metabolites in leaves, stems of roots, root transudation, and canopy structure (Pastor et al. 1984). Variation in these traits of plants influences mineral availability and microhabitats for soil microbes, which further affects mineralization and decomposition activity (Bever et al. 1996; Paul and Clark

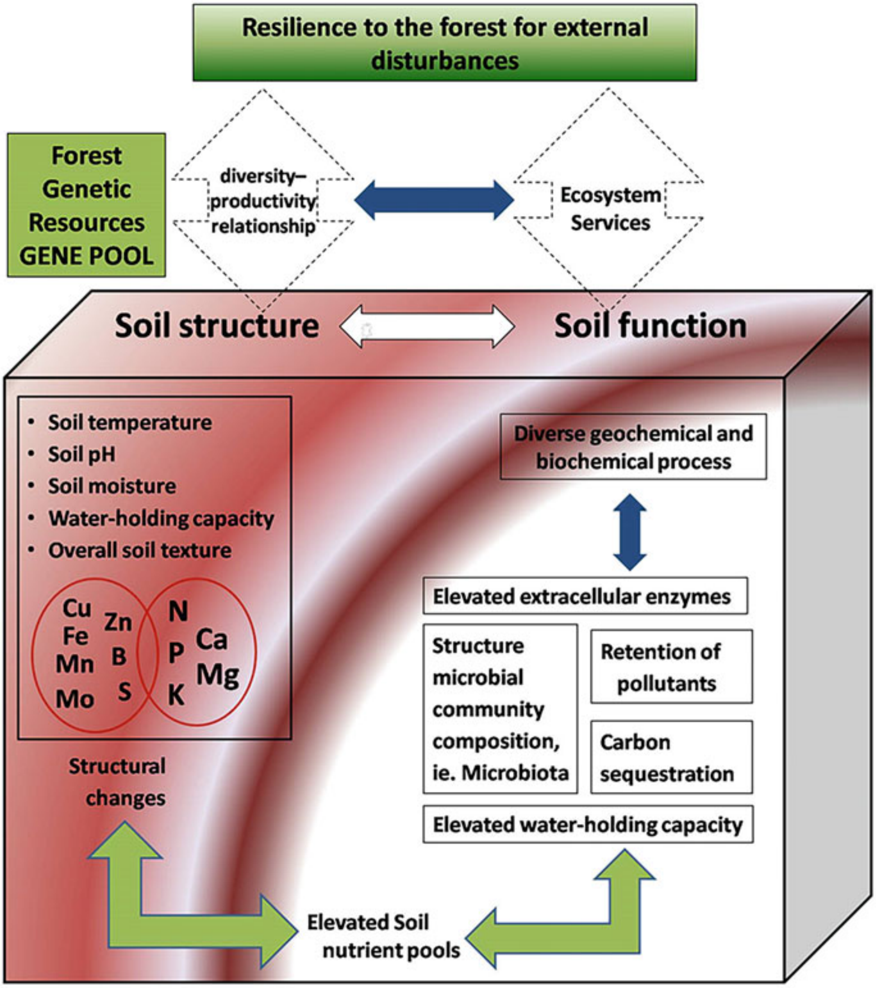

Fig. 7.1 Different components of soil ecosystem and their interplay with gene pool for forest ecosystem sustenance

1996; Priha et al. 2001; Bartelt-Ryser et al. 2005; Grayston and Prescott 2005). Thus, species diversity can be utilized for the prediction of ecosystem processes such as productivity or soil processes (Waldrop et al. 2006). For instance, in response to phosphorus deficiency, plants use a range of mechanisms in amalgamation with microbial processes to intensify the mobility and bioavailability of soil phosphorus (Richardson et al. 2009).

The interactions between plants and microbes can be affected by a multitude of processes and species interactions, namely nutrient-, water-, and light-related interactions, along with biotic interactions (e.g., reduced pest damage) (Forrester and Bauhus 2016). Variations in crown architecture and canopy structure that influence light absorption, along with differences in physiology or phenology that influence the efficiency of sunlight use and the timing of light absorption, are examples of light-related interactions, whereas symbiotic nitrogen and phosphorus fixation, elevated rates of nutrient cycling, or where the abundance and composition of mycorrhizae change under mixtures, leading to greater uptake of different forms of a given nutrient, are mostly examples of nutrient-related processes (Lovelock and Ewel 2005; Richards et al. 2010).

In the soil, phosphorus exists in various inorganic and organic forms, and plants' use of these various P types is complicated and poorly understood (Richardson et al. 2009). Recognizing how species composition influences the existence of various P types (e.g., adsorbed inorganic P, active inorganic P, adsorbed organic P, and occluded inorganic P) and vice versa, as well as how various types influence plant variability, may help to create long-term solutions to soil phosphorus shortages. Similarly, elevated aboveground litterfall and belowground fine root mortality in species-rich plant communities may raise soil microbial biomass due to the greater amounts of carbon and nutrient available resources for soil microorganisms (Lange et al. 2015; Khlifa et al. 2017; Ma and Chen 2018).

The changes in plant diversity in forests could affect the production, as well as the distribution, of organic molecules in the detritus that restrict, and thus regulate the composition and function of heterotrophic microbial communities (Zak et al. 2003). Plants do so as exudates from plant roots, including trees, contain a wide range of carbohydrates, organic acids, and other signaling molecules, promoting a diverse microbial community in the root-soil zone. For example, acidifying species of trees encourage the presence of a large number of acidophilic bacterial taxa in the soil (Uroz et al. 2016). Likewise, pH variations resulting from exudates of Acer, Betula, Fagus, and Quercus spp. influence members of the Rhizobiales and Burkholderiales orders, instead of just soil characteristics or regional differences (Landesman et al. 2014). Nevertheless, since Gram-positive bacteria have thicker cell walls and the ability to shape spores in drought environments (Berard et al. 2011; Escobar et al. 2015), the reduced soil moisture related to lower plant diversity can enhance the Gram-positive: Gram-negative bacteria ratio.

The microbial biomass and respiration react similarly to environmental changes (Holden and Treseder 2013; Zhang et al. 2018a, b) and plant species diversity changes (Strecker et al. 2016). Apropos, plant diversity can affect the carbon-to-nitrogen (C: N) ratio and respiration of soil microbes. Since fungi have a larger C: N ratio than bacteria, soil microbial C: N ratio can increase with plant diversity through increased fungi: bacteria ratio (Lange et al. 2014; Mouginot et al. 2014; Chen et al. 2016). The association between and among plant species, as well as associated microorganisms growing together, has been shown to encourage the growth of certain tree mixes (Thompson et al. 2014), implying that more diversity should be promoted.

7.7.2 Tree Genotypic Variation

Genetic variation can have interspecific population effects that affect associated plants (Iason et al. 2005), arthropods (Crutsinger et al. 2006; Johnson et al. 2009), and soil microbial communities and their activities (Madritch et al. 2009). Individual tree genotypes and genotypic diversity play an important role in altering the nature of forest communities by facilitating covariance across various functional groups such as microorganisms, lichens, and invertebrates (Lamit et al. 2015). Plant genetic and trait variation affect substrate availability or conditions for soil microorganisms, which can impact microbial community structure and behavior (Grayston and Prescott 2005), resulting in specific communities on individual plants. These associations between cultures can affect the structure and function of the soil. The links between plant traits and belowground processes in terrestrial ecosystems (Wardle et al. 2004) suggest that genetic variation in dominant plant species could influence the associated belowground soil microbial community and the ecosystem processes that microorganisms mediate. For example, different tree genotypes of the *Populus angustifolia* and *Populus balsamifera*can support various soil microorganisms, leaf pathogens, foliar fungi, twig endophytes, lichens, and arthropod populations (Bálint et al. 2013). It has also been mentioned that the tree genotype-specific organism communities are heritable and stable over time (Keith et al. 2010). The magnitude of this community-shaping impact induced by tree genotype, on the other hand, varies depending on the tree species, environmental factors, as well as the functional group in concern. Nevertheless, how tree genotypes and genotypic diversity affect ecosystem functions is still unclear.

Soil microbial communities, comprised of bacterial, archaeal, and fungal groups, along with the protists, regulate plant diversity and productivity (van der Heijden et al. 2008). As soil heterotrophic microbial communities trigger critical processes that regulate ecosystem carbon (C) and nitrogen (N) cycling, they can reflect a mechanistic connection between plant diversity and ecosystem function (Zak et al. 2003). Recent research has suggested significant spatial heterogeneity in the distribution of soil microbial diversity and functional potential (Delgado-Baquerizo et al. 2018) as well as major drivers of bacterial alpha-diversity across habitats (Bahram et al. 2018). Even so, alpha diversity belowground is not always associated with alpha diversity aboveground (Cameron et al. 2019). Soil microbial diversity is only weakly associated with plant diversity, particularly for bacteria and fungi. Therefore, emphasizing plant diversity may not be useful in identifying soil microbiome responses to factors such as climate change (Prober et al. 2015) or biodiversity loss (Fanin et al. 2019). As a result, while plant diversity impacts soil microbial biomass (Chen and Chen 2018) and plant community compositions can strengthen microbial community estimates, the global variation in microbial populations defined by plant community structure is poor (Leff et al. 2018).

7.8 Conclusion

Self-organizing forest ecosystems are key providers of many ecosystem services such as climate regulation, biomass production, and water supply. However, for the sustenance of these vital services, different components of forests, viz. (1) soil, (2) microorganisms, (3) animals, and (4) plants, interact together in a efficient manner. Among different components and interactions, the plant-microorganisms–soil interaction plays a pivotal role in the diverse geochemical and biochemical processes, especially the maintenance and regulation of nutrient pools and carbon sequestration. The diverse plant's gene pool on the forest floor influences the soil structure and ultimately the soil functions, via variation in the quality and quantity of leaf litter produced, which creates a genotypic difference in litter decomposition and nutrient release. The genetic diversity in the existing gene pool with inter- and intraspecies differences in traits such as plant growth rate, productivity, level of secondary metabolites, carbohydrates, organic acids, signaling molecules in exudates influences the soil physical parameters (structure) such as pH, soil moisture, etc., and therefore structures microbial communities belowground by changing the availability of substrates. The diverse soil communities belowground in turn create a multitude of dynamic microenvironments for various soil functions, such as the decomposition of organic matter and thus the mineralization of nutrients. Apropos, exploration and understanding of the complex forest-soil relationship on a temporal and spatial scale are vital for environmental monitoring and management.

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Part II

Forests and Sustainability Concerns

Plant–Herbivorous Insect Interactions in Forest Ecosystems: Overview and Perspectives to Mitigate Losses

8

Plant–Herbivorous Insect Interactions in Forest Ecosystems: Overview and Perspectives to Mitigate Losses

Eduardo Soares Calixto and Philip G. Hahn

Abstract

Evolutionary ecological studies have postulated that interactions between species are critical drivers of species diversification, in which each type of interaction promotes diversification in different ways. For instance, studies have suggested that antagonistic associations, such as plant–herbivorous insect interactions, can be paramount for the diversification process via coevolution between offensive and defensive traits that mediate interactions. In turn, plant–herbivore interactions, and the resulting diversification of traits, are therefore important determinants of community structure and dynamics. Here, we provide a general overview of how plant–herbivorous insect associations can be important for promoting diversity and maintaining ecosystem dynamics and structure. To this end, we start the chapter by presenting an overview of plant–herbivorous insect interactions, with a background of how evolutionary ecological studies about ecological interactions are important to understand the processes that drive species diversity. Then, we discuss the coevolutionary process between plants and insects by describing how plant–herbivorous insect coevolution can promote species diversity and shape ecosystems, and the potential mechanisms by which plants and herbivores might influence the ecosystem structure and biodiversity, which can act as a proxy for conservation measures. Next, we discuss the role of insect herbivory in shaping forest restoration outcomes, and how plant-provided resources mediating the protective mutualism can act as a biodiversity enhancer. Finally, we end the chapter by suggesting some novel and underrepresented perspectives within the topic, supporting researchers and policymakers to focus

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their efforts on certain measures to successfully maintain and protect biodiversity in different ecosystems.

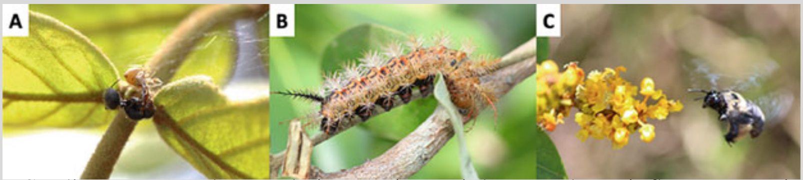
Keywords

Herbivore · Antagonism · Janzen–Connell hypothesis · Density dependence · Ecosystem engineering · Biodiversity · Coevolution · Forest restoration

8.1 Introduction

Since the beginning of evolutionary ecological studies, different types of interactions have been associated with species diversification, in which the diversification process has been thought to be promoted by different types of interactions (Darwin 1859; Dobzhansky 1950; Ehrlich and Raven 1964). With the advancement of studies on such a topic, there is evidence that the coevolutionary diversification process occurs in different intensities according to the type of interaction (see Box 8.1). For example, some theoretical studies have suggested that antagonistic associations, such as competition (i.e., both species are negatively affected by the interaction) and predation or herbivory (i.e., one species is negatively affected and one benefits), can be paramount for the diversification process, while mutualistic interactions (i.e., both species benefit) may or may not lead to coevolutionary diversification (Doebeli and Dieckmann 2000; Yoder and Nuismer 2010; Bronstein 2021). In fact, we can see a considerable amount of empirical studies showing diversification driven by coevolution in competitive interactions between species who occupy similar trophic levels (Schluter 2000; Yoder et al. 2010). This same proportion of studies is not seen for diversification driven by species coevolution at different trophic levels, with a low, but an increasing number of empirical studies showing diversification through antagonistic interactions (e.g., Becerra 2007; Futuyma and Agrawal 2009; Janz 2011), such as herbivory, and even less for mutualistic interactions (see Hembry et al. 2014; Bronstein 2021).

Box 8.1 Different Types of Interactions Associated with the Coevolutionary Diversification



Studies suggest that each interaction might somehow influence species diversification, where some interactions have a strong intensity in driving

(continued)

Box 8.1 (continued)
the coevolutionary diversification process than others. Current studies have supported three different interactions (competition, predation/herbivory, and mutualism), but the number of studies among them are significantly different. There are a considerable number of studies regarding the competitive coevolution between species in the same trophic level (A), and a representative growth in the number of studies regarding antagonistic (e.g., herbivory; B) and mutualistic interactions (e.g., pollination; C). Different mechanisms have been proposed and shown as a support to the stable coexistence among species that occupy the same trophic level of given ecological network of interactions (Chesson 2000). Among these stabilizing mechanisms of coexistence is the niche specialization, both in time and in space. Recently, Lange et al. (2021) evaluated different mechanisms based on niche specialization with great potential for promoting stable coexistence between organisms (in this case, foliage-dwelling ants and spiders) of the same trophic level that forage on extrafloral nectar-bearing plants. Lange et al.'s results suggest that it is likely that ants and spiders coexist stably due to a spatial and temporal niche partition, suggesting a decrease in competition and potential specialization, resulting diversification. Indeed, there is evidence that herbivory can drive coevolutionary diversification, but it is not totally clear how this occurs. As producers, i.e., the first trophic level in many ecological food chains representing a food resource for herbivores, plants can be chemically and structurally diverse. This scenario in which plants have developed chemical defenses against the attack of herbivores has been the focus of studies considering coevolutionary diversification for years (Becerra 2007; Futuyma and Agrawal 2009; Marquis et al. 2016; Maron et al. 2019). See more details in the subsection *2.2. Coevolutionary patterns*. Conversely to the other two interactions, mutualistic coevolution has been a long-standing puzzle in ecological and evolutionary studies due to uncertainty of whether and how it can promote diversification (Vandermeer and Boucher 1978; Axelrod and Hamilton 1981; Bronstein 2021). Some empirical studies have given support to the coevolutionary diversification driven by mutualistic interactions, such as the pollinator–plant coevolution which leads to reproductive isolation (Thompson 2005a, 2013; Godsoe et al. 2010). Indeed, pollination is extremely likely to drive the coevolutionary diversification by promoting mutualistic coevolutionary speciation, since animal pollinators "control" the amount of gametes withdrawn and deposited in many cross-pollinated plants (Thompson 1994). Photos: ES Calixto.

A result of diversification is that it can lead to patterns of species coexistence (Chesson 2000). Different species can coexist at the same place and time through two main mechanisms: *stabilizing forces*, which are mechanisms that promote coexistence of species by increasing intraspecific competition compared with interspecific competition, in such a way that species' population sizes are able to increase at low density; and *equalizing forces*, which are mechanisms that promote coexistence by reducing average fitness difference or the relative competitive ability between species when niche differentiation is not present (Chesson 2000; Adler et al. 2007; Levine and HilleRisLambers 2009). Many empirical studies have focused on the study of niche partitioning (Gilbert et al. 2008; Finke and Snyder 2008; Staples et al. 2016; Rey et al. 2017; Lange et al. 2021), a stabilizing mechanism, as a driver of species coexistence and biodiversity enhancer. However, one potential mechanism that can increase biodiversity is promoted by specialist natural enemies, such as herbivores. Although there is a great diversity of herbivore groups, we focus our chapter in the most abundant group of organism in terrestrial ecosystem, *the insects*, which is represented by approximately one million described species (50% of the total species of living beings described so far; Grimaldi and Engel 2005; Stork et al. 2015). Together with plants, these two groups of organisms make up the majority of living and macroscopic species on Earth and therefore are paramount for the functioning of ecosystems.

Understanding the dynamics of trophic cascades in different ecosystems has been a challenge for researchers from different fields for many years (May 1973; Post 2002; Dyer 2011), in which one of the main focus of the study is the degree of generalization or specialization (see Reagan and Waide 1996; Blüthgen et al. 2003). Plants, namely primary producers, are the first trophic level and are considered regulatory organisms of a whole food chain, a process known as a bottom-up effect. Plant consumers, namely herbivores, represent the second trophic level in food chains and are in a close relationship with plants (Fig. 8.1), directly influencing their fitness and survival, a process known as a top-down effect. Combined, bottom-up and top-down effects are forces within food webs directly and indirectly shaping and maintaining biodiversity and ecosystem dynamics (Price et al. 2011).

Here, we provide a general overview of how plant–herbivorous insect associations can be important for promoting diversity and maintain ecosystem dynamics and structure, ultimately representing an excellent tool for conservation measures. To this end, we start the chapter presenting an overview about plant–herbivorous insect interactions, describing the history behind the interaction between these two organisms. Then, we provide a background of how studies focusing on the ecology and evolution of interactions are important to understand the processes that drive species diversity. We discuss the coevolutionary process between plants and insects by describing how plant–herbivorous insect coevolution can promote species diversity and shape ecosystems, and the potential mechanisms by which plants and herbivores might influence the ecosystem structure and biodiversity, which can act as proxy for conservation measures. We also provide an overview about the role of insect herbivory in shaping forest restoration outcomes, and how plant-provided resources mediating the protective mutualism can act as a biodiversity enhancer. Finally, we conclude the chapter suggesting some novel and underrepresented perspectives within the topic, supporting researchers and policymakers to focus their efforts on certain measures to successfully maintain and protect the biodiversity in different ecosystems.

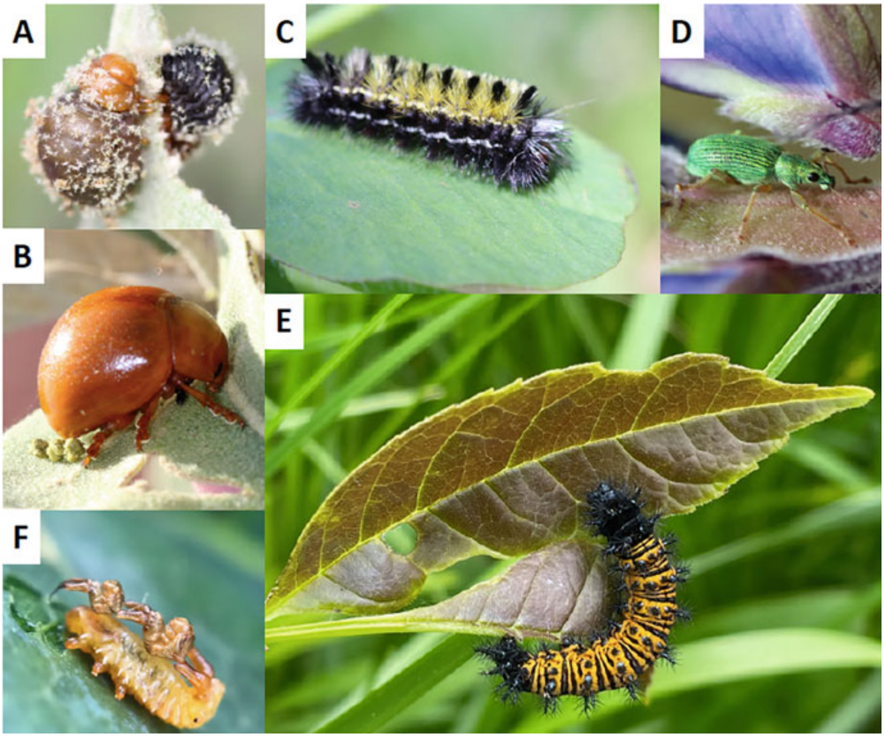


Fig. 8.1 Plant–herbivorous insect interactions. (**a**, **b**) Chrysomelidae (Coleoptera) larvae (**a**) and adult (**b**) feeding on *Solanum lycocarpum* (Solanaceae), (**c**) Erebidae (Lepidoptera) larva, (**d**) *Polydrusus formosus* (Coleoptera) foraging on *Lupinus perennis* (Fabaceae), (**e**) *Euphydryas phaeton* (Lepidoptera) larva feeding on a host plant, (**f**) Chrysomelidae (Coleoptera) larva feeding on a host plant. (Source: photos by ES Calixto)

8.2 Plant–Herbivorous Insect Interaction

8.2.1 Brief History

Fossil records have indicated that the first interactions between insects and plants occurred about 400 million years ago (Labandeira 1998; Schoonhoven et al. 2005; Misof et al. 2014). These interactions were probably antagonistic (herbivory), in which insects fed on specific plant tissues (such as spores) or had some specific structure for perforation and suction of plant tissues (Labandeira and Sepkoski 1993; Labandeira 1998; Schoonhoven et al. 2005). Although plants appeared earlier than insects, it was only in the Cretaceous period that the largest group of existing plants, the angiosperms, appeared, just when insects were abundantly present (Labandeira and Sepkoski 1993; Grimaldi and Engel 2005; Schoonhoven et al. 2005). Concomitantly to this considerable increase in plant diversity, there was a great diversification of insects, supporting the hypothesis of a close relationship between these two groups. Thus, this close relationship may have resulted and will likely continue to result directly in the ecosystem's biodiversity patterns (Kukalová-Peck 1991; Thompson 1997; Labandeira 1998; Del-Claro and Torenzan-Silingardi 2012; Del-Claro and Torezan-Silingardi 2021).

Interactions between insects and plants, whether mutualistic or antagonistic, correspond to most ecological interactions, representing the structuring basis of ecosystems. However, the study of the interaction between these two organisms emerged in the late nineteenth century (e.g., Packard 1890). Since then, the number of studies in this topic has been gradually increasing, with a considerable increase in the last 40 years. Between the 1960s and 1990s, important studies emerged providing and expanding our knowledge of various theories and hypotheses about the relationship between plants and herbivorous insects and the consequences of these interactions for the ecosystem as a whole (Ehrlich and Raven 1964; Berenbaum 1983; Marquis 1984; Thompson 1989). After the 1990s, especially in the past 20 years, we have seen a steady increase in the interest in the mechanisms responsible for the patterns of biodiversity and maintenance of ecosystems (Chesson 2000; Del-Claro 2004; Thompson 2005b). Recently, many studies have sought to disentangle the mechanisms responsible for driving and maintaining the biodiversity patterns (Del-Claro and Torezan-Silingardi 2021 and references therein).

8.2.2 Coevolutionary Patterns

The reciprocal evolution between interacting taxa is widely considered as one of the main drivers of species diversification (Thompson 2005a, 2009). Since the nineteenth century, naturalists have already highlighted the importance of animal–plant interactions in an evolutionary perspective (Darwin 1859; Wallace 1889). For instance, Darwin used the term "*coadaptation*" for describing a reciprocal adaptation of morphological structures between different animals, *i.e.*, adaptation of a given morphological part of an organism to another. In 1924, Brues suggested that the close relationship between some herbivores and their plant hosts might be explained by a reciprocal evolution of these both groups: "*Parallel evolution of insects and their food-plants where groups are concerned rather than isolated species is, however, much more plausible and the probability of this having taken place in many instances appears greater as we examine in detail the food habits of certain insects*" (Brues 1924).

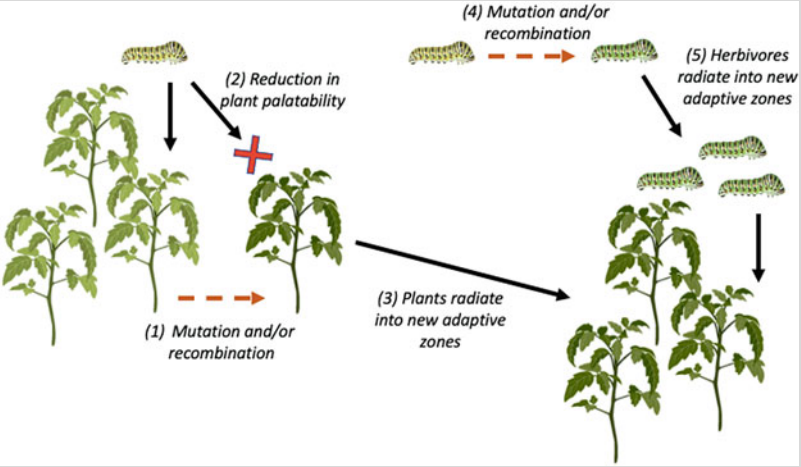
Although studies have hypothesized the reciprocal evolution between herbivores and their host plants, the term "*coevolution*" was only coined in 1964 by Ehrlich and Raven in a coevolutionary study between butterflies and plants (Ehrlich and Raven 1964). Ehrlich and Raven's study proposed that a coevolutionary "*arms-race*" between insect herbivores and their host plants contributed to the species diversification, influencing speciation rates, a hypothesis known as "*escape and radiation coevolution*" (term coined by Thompson 1989; Box 8.2). The escape and radiation coevolution process involves the evolution of a new defense in the host plant, allowing it to "*escape*" from herbivores. Then, the host plant can "*radiate*" into differing species that fill unique niches. Subsequently, an herbivore which has evolved ways to surpass or detoxify the plant secondary compounds can speciate and diversify on the newly radiated plants (Box 8.2). Some studies have addressed the radiation of insects on plants (e.g., Farrell and Mitter 1994; Winkler et al. 2009; Fordyce 2010; Rainford and Mayhew 2015), but the conclusions about the role of plant defense in plant diversification are still incipient.

Box 8.2 Escape and Radiation Coevolution

In 1964, Ehrlich and Raven published the paper "Butterflies and plants: a study in coevolution," in which they introduced the term "coevolution" (Ehrlich and Raven 1964). By discussing the interaction between different species of butterflies and their association to different host plants species, which present different sets of secondary compounds, they suggested that the reciprocal evolution between herbivores and their host plant greatly contributed to the species diversification, influencing speciation rates and biodiversity patterns. This process of diversification was later termed by Thompson (1989) as the "escape and radiation coevolution," a coevolutionary "arms-race" between insect herbivores and their host plants. According to Thompson (1989), the escape and radiation coevolution is made up of five steps: (1) production of one or more novel secondary compounds by the host plant through mutation and/or recombination; (2) these new compounds reduce plant palatability to herbivorous insects, favoring natural selection; (3) plants presenting the new compounds radiate into new adaptive zones in enemy-free spaces, that is, free of their former herbivores; (4) a mutation and/or recombination appears in an insect population, which make insects able to surpass the plant defense, *i.e.*, the new secondary compounds; (5) these insects adapted to overcome plant secondary compounds enter in a new adaptive zone and radiate in numbers of species onto the plants containing the novel secondary compounds, ultimately resulting in the formation of new taxon or taxa of herbivores. The process then repeats.

(continued)

Box 8.2 (continued)



Ehrlich and Raven's classical study has boosted different studies in coevolution, especially between herbivorous insects and their host plants. In a general view, their study suggests that the reciprocal evolution between plants and their insects' herbivores might be one of the potential drivers for the great diversification of both groups. Since then, studies about coevolution have attempted to show how reciprocal evolution (either in mutualistic or in antagonistic interactions) has influenced and shaped the patterns of divergence among related species within communities. For instance, some plant–pollinators studies have focused on the patterns of floral traits and plant phenology in different communities (see Aizen and Vázquez 2006; Vázquez and Aizen 2006; also see Del-Claro et al. 2018 for the ant-plant mutualism). Similarly, there has been a considerable increase in the number of studies focusing on the role of plant–herbivore coevolution on community patterns of plant diversification (e.g., Thompson 2005b; Becerra 2007; Marquis et al. 2016; Maron et al. 2019), as well as of theories discussing the coevolutionary pattern along spatial scales, such as the geographic mosaic theory of coevolution (GMTC) (Thompson 2005a, b, 2009, 2013).

The essence of GMTC is to provide a way to visualize the coevolutionary process in real populations and species by incorporating the minimum components of population biology for better understanding the coevolution in an ecological and evolutionary framework. The GMTC is based on three main assumptions: Species are compilations of populations genetically distinct; interacting species often differ in their geographic ranges; and the ecological outcomes of interactions among species are different across different environments (Thompson 2005a, b, 2009). According to Thompson, the GMTC argues that natural selection can act on three different sources of variation, which might influence the interaction among species, ultimately resulting in coevolutionary patterns. These three sources of variation are as follows:

- *Geographic Selection Mosaics*: Genes are expressed in different ways across environments (Gene x Environment interactions; G x E), in which the way one species influences the evolutionary fitness of another species will depend upon the environment where they are inserted. In this perspective, the geographic selection mosaics will occur when the structure of natural selection on coevolutionary interactions differs among environments (e.g., high- vs. low-resource availability regions). This is a case of genotype (G) by genotype (G) by environment (E) interaction (G x G x E). For instance, a given interaction can interchange from antagonistic to mutualistic across different environments (Johnson et al. 2010).
- *Coevolutionary Hotspots*: Coevolutionary hotspots are places where there is a great intensity of reciprocal selection (i.e., there is a G x G interaction on the fitness of the interacting species). These hotspots are expected to be embedded in a geographic matrix of coevolutionary cold spots. In coevolutionary cold spots, selection is non-reciprocal, and an example of this process is when only one of the interacting species occurs.
- *Trait Remixing*: Set of different processes (e.g., new mutations, genomic alterations, gene flow among populations, genetic drift, populations extinction, or recolonizations dynamics) that can potentially influence the spatial distribution of coevolving genes and traits. For instance, the combinations of the aforementioned processes influence the distribution of genotypes within a local population and among populations.

8.3 Potential Mechanisms Associated with Diversification

8.3.1 The Janzen-Connell Hypothesis

Proposed independently by Daniel Janzen and Joseph Connell, the Janzen-Connell (J-C) hypothesis (Janzen 1970; Connell 1971) postulates that the survival of seeds and seedlings by the action of host-specific herbivores, pathogens, and other types of natural enemies (as known as "predators") is distance- and/or density-dependent: Areas close to the seed-producing plant are inhospitable for the establishment of a new generation of the same plant species. Therefore, these host-specific predators prevent a given species from dominating the ecosystem, ultimately promoting the establishment of other species. Although this J-C hypothesis mainly focuses on impacts caused by predators due to distance and density, the ideas related to density dependence had a substantial influence on theoretical developments in ecology, such as negative density dependence caused by competition or some concepts embedded in modern coexistence theory. Negative density dependence occurs when population growth is impaired by higher conspecific densities, predators, and competition. In this last case, it is expected strong intraspecific competition for limited resources when conspecifics are present in high densities.

The J-C hypothesis has been proposed as one of the mechanisms promoting diversity in both tropical and temperate forests (Comita et al. 2010; Terborgh 2012; Forrister et al. 2019). For instance, Comita et al. (2014) observed overall significant conspecific distance and density dependence effects on the survival of plant communities worldwide. However, few studies have addressed which mechanisms are responsible for driving the negative distance and density dependence process (Comita and Hubbell 2009; Bagchi et al. 2010, 2014; Metz et al. 2010; Terborgh 2012). Recently, Forrister et al. (2019) observed that herbivores are the primary mechanism driving negative density dependence at the sapling stage of coexisting *Inga* (Fabaceae) congeners in a tropical forest. All these results support the J-C hypothesis and show that the interaction between plants and herbivorous insects can be one of the most important drivers of species diversity in different ecosystems.

8.3.2 Ecosystem Engineers

The term ***ecosystem engineering*** is often described as the effects caused by a single organism in different spatial and temporal scales (Jones et al. 1994); however, it can also be used to describe the effects of plant–animal interactions on the ecosystem, as a way to disentangle their non-trophic effects (see review in Calixto et al. 2021b). There are different ways to classify an ecosystem engineer, but the most common division is when an organism modifies its own structure, *autogenic engineers*, and when an organism modifies some external structure, *allogenic engineers*. Insects and plants can be present on both divisions. For instance, many lepidopterans larvae modify the format and structures of leaves to build shelters that can be used for different animals (Lill and Marquis 2003; Velasque and Del-Claro 2016; Fig. 8.2); ants and termites can alter soil properties and structure influencing nutrient availability and aeration (Folgarait 1998; Bignell 2006). Regarding plants, plants can modify the environment with their own structure, creating shades, microclimates, forming specialized structures that directly and indirectly influence positively the presence of other organisms (Kitching 2000; Arredondo-Núñez et al. 2009).

Considering the plant–herbivorous insect interaction, there are different ways that the ecosystem engineering framework can be applied. When dealing with ecological interactions, ecosystem engineering is the result of the interaction between organisms (Calixto et al. 2021b). For instance, we can indicate the shelter-building insects (Fig. 8.2a, b) and gall-inducing insects (Fig. 8.2c–e). Studying the interaction between the caterpillar from the genus *Pseudolteulphusa* (Gelechiidae) and the plant species *Quercus alba*, Lill and Marquis (2003) observed that the leaf shelters constructed by the caterpillars act as a resource for a myriad of other organisms by creating a microclimate that helps make the abiotic conditions better, in addition to increase food quality and protect against enemies. In another example, Velasque and Del-Claro (2016) observed in the Brazilian Cerrado that the leaf shelters made by *Cerconota achatina* (Oecophoridae) in the Malpighiaceae plant, *Byrsonima*

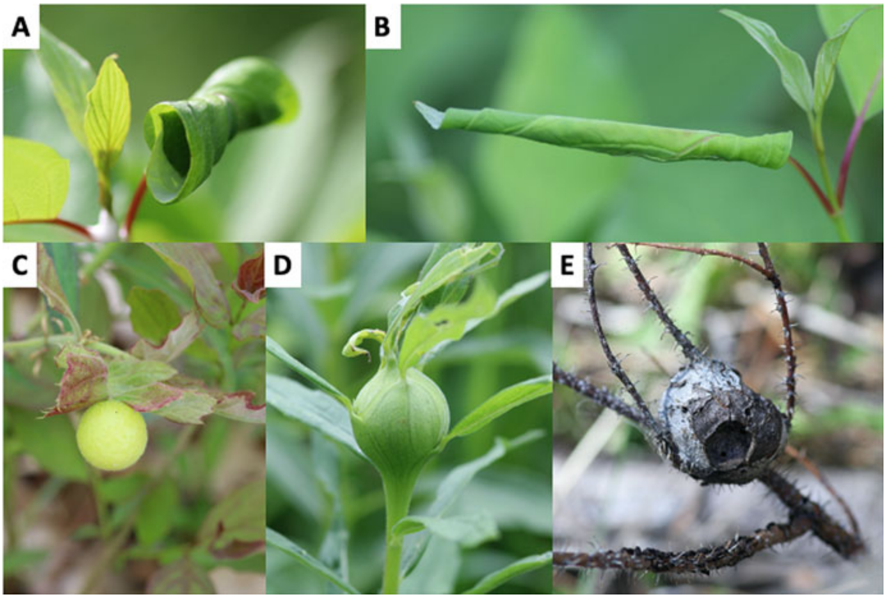


Fig. 8.2 Examples of plant–herbivorous insect interactions which the ecosystem engineering framework can be applied to. (**a**, **b**) Shelter built by a leaf roller. (**c**, **d**) gall induced by the presence of a gall-inducing insect. (**e**) vacant gall which can be used by different organisms, acting as an ecosystem engineer. (Source: photos by ES Calixto)

intermedia, can provide shelter for 153 other arthropods. By modifying these plant structures, shelter-building insects increase vacant spaces to other organisms, in addition to alter leaf physio-chemical properties, which can influence the presence of other organisms (Jones et al. 1994, 1997; Lill and Marquis 2003; Cornelissen et al. 2016; Calixto et al. 2021b).

Gall-inducing insects are insects that induce plant host cellular differentiation leading to chemical and physical modifications in plant tissue (Fukui 2001; Cornelissen et al. 2016). These structures can provide habitat, protection, food, and many other advantages for the gall-inducing insect, as well as for any other organism that inhabit the gall after the gall-inducing insect leaves (Price et al. 1987; Stone and Schönrogge 2003). For instance, Wheeler and Longino (1988) found eight species of ants in empty galls induced by the mealy oak gall wasp, *Disholcaspis cinerosa* (Cynipidae). Waltz and Whitham (1997) also observed a decrease of 32% of the richness and 55% of abundance of arthropods after removing the galls induced by the aphid *Pemphigus betae* (Aphididae) in cottonwoods.

8.4 The Role of Insect Herbivory in Shaping Forest Restoration Outcomes

Forested systems face numerous threats that have affected and will continue to affect biodiversity and ecosystem dynamics. Ecological restoration is the practice of increasing the diversity, functioning, and services of degraded ecosystem, although the restoration outcomes are highly variable (Suding et al. 2015; Brudvig and Catano 2021). Conceptual and theoretical models inspired by plant–herbivorous insect interactions, including coevolution, the J-C hypothesis, and others, can be used to not only understand mechanisms maintaining diversity, as described above, but also to inform best practices for restoring forest diversity (Temperton et al. 2017). Specifically, the concepts of distance dependence herbivory rates may be key for understanding how insect herbivores determine the outcome of restoration. For example, most forest patches are highly isolated with considerable amounts of edge (Haddad et al. 2015). Distance to the nearest source patch of herbivores (Harvey and MacDougall 2015), or other factors that influence spatial habitat selection such as habitat edges (Evans et al. 2012; Hahn et al. 2015), has been shown to influence herbivory rates in forest habitats. Plant defenses are another factor that can mediate how herbivores impact restoration outcomes. For example, in restoring pasture to tropical forest, Massad et al. (2011) showed that plant species with certain types of toxic chemicals improved their successful establishment by resisting herbivory. Overall, the guiding principles of plant–insect coevolution and J-C hypotheses have clear applications for the management and restoration of forest ecosystems.

In temperate forests, the understory is often the most diverse component, contributing significantly to forest biodiversity and ecosystem processes (Gilliam 2007). However, much like forests generally, a number of factors threaten biodiversity of understories, including fragmentation, invasive species, and herbivores to name a few (Flinn and Vellend 2005). White-tailed deer are the herbivore that have had perhaps the most well-documented negative effects on understory communities (Rooney and Waller 2003; Côté et al. 2004), but insects and other arthropods can also strongly impact understory population and community dynamics (Ehrlen 1995; Hahn et al. 2011; Hahn and Dornbush 2012; Munique and Calixto 2018). For example, molluscan herbivores influenced seedling establishment and community structure more strongly than deer herbivory in a temperate forest (Liang et al. 2019). Thus, a consideration of how insect herbivores might shape forest understory diversity and potentially impede restoration is of growing concern.

The longleaf pine ecosystem in the southeastern USA provides an interesting case study of how herbivory can affect understory restoration. The herbaceous understory is one of the most diverse systems outside the tropics and is maintained by frequent low-intensity fires (Walker and Peet 1984). However, this ecosystem has been largely destroyed, and what remains is regenerating on historic agricultural lands and is severely fire suppressed. The potential to support high diversity has made the longleaf pine ecosystem a priority for restoration (Noss et al. 1995; Walker and Silletti 2006). Grasshoppers are one of the most abundant herbivores in the longleaf pine understory (Knight and Holt 2005; Hahn and Orrock 2015a) and have the potential to impact plant performance and community dynamics. For example, one study found that grasshopper herbivory reduced the performance of a native plant most strongly in sites degraded by fire suppression and historical agriculture compared with undisturbed remnant sites (Hahn and Orrock 2015b). One potential mechanism for increased herbivory in degraded sites was that these sites lack a diverse understory layer (Brudvig et al. 2014, 2021), thus making palatable native plants more apparent to herbivores (Hahn and Orrock 2015b, 2016b). Restoration of degraded sites may therefore be highly susceptible to herbivory. Follow-up studies supported this hypothesis, reinforcing herbivory as a major factor potentially limiting restoration effects, but also showed that additional restoration activities, mainly overstorey thinning aimed at reversing the effects of fire suppression, enhanced the survival of desirable native plants (Hahn and Orrock 2016a). Transplanted seedlings had lower herbivore-caused mortality at sites where overstorey thinning was implemented compared with fire-suppressed sites that possessed a dense canopy (Hahn and Orrock 2016a). Thus, this study highlights that multiple restoration activities, namely propagule addition coupled with overstorey thinning, may be necessary to overcome the biotic stressors of herbivory in degraded landscapes. Clearly, more research is needed in this area and there is clear scope for future studies to consider potential synergies among multiple restoration strategies.

8.5 Biodiversity Enhancement Around Plant-Provided Resources in the Protective Mutualism

Plants have evolved different types of defenses to decrease or totally eliminate the damages caused by herbivores, such as chemical (e.g., terpenes), mechanical (e.g., toughness, spines, thorns), and biotic (e.g., natural enemies of herbivores) defenses (Fürstenberg-Hägg et al. 2013; Calixto et al. 2015). In this last case, plants offer some sort of rewards in exchange for defense against potential herbivores, an interaction known as protective mutualism (Calixto et al. 2018a; Moura et al. 2021). This biotic defense is usually represented by arthropods, such as wasps (Alves-Silva et al. 2013) and spiders (Stefani et al. 2015; Del-Claro et al. 2017; Sousa-Lopes et al. 2019), but mainly ants (Del-Claro et al. 2016; Calixto et al. 2018a; Moura et al. 2021). Ant–plant interactions have been paramount for a better understanding of mutualisms (Bronstein 1998; Del-Claro 2004; Rico-Gray and Oliveira 2007; Del-Claro and Torezan-Silingardi 2009), even when ants exceptionally act as pollinators (Beattie 1985; Del-Claro et al. 2019). Thus, we should also focus our efforts on this kind of interaction to better understand their role as a biodiversity enhancer and community dynamics.

According to the level of association to ants, specialized or not specialized, plants can be classified as myrmecophytes and myrmecophilous (Rico-Gray and Oliveira 2007; Calixto et al. 2018a). Myrmecophytes have modified structures which enable ants to colonize and nest. These structures arise as modifications of different plant parts (Fig. 8.3a), such as leaves, trunk, bulbs, or roots, commonly called domatia

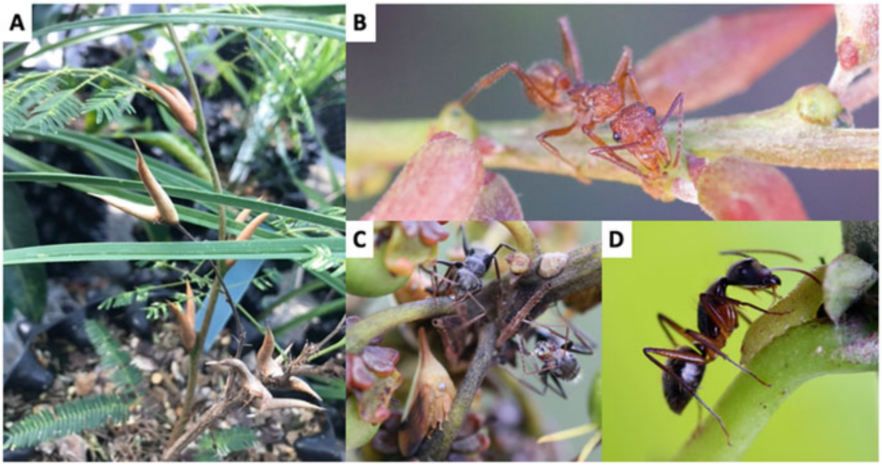


Fig. 8.3 (**a**) *Acacia* (Fabaceae) plant with hollowed-out thorns (domatia), where ants can nest. (**b**) *Ectatomma tuberculatum* (Ectatomminae) ant feeding on the extrafloral nectar of *Bionia coriacea* (Fabaceae). (**c**) *Camponotus crassus* (Formicinae) ants tending *Echenopa concolor* (Hemiptera). Note the small drops of *honeydew* on the ants' mandibles. (**d**) *Camponotus renggeri* (Formicinae) tending a sugar-rich liquid-producing caterpillar. (Source: photos by ES Calixto)

(singular: "domatium"). Only in the Neotropics, myrmecophytes are distributed in 14 families presenting approximately 250 species (Benson 1985). This diversity of myrmecophytes is associated with a high diversity of ants, directly influencing biodiversity patterns in several regions. Probably, the best-known example of association between myrmecophytes and ants is the interaction between swollen-thorn *Acacia corginera* (Fabaceae) and *Pseudomyrmex ferrugineus* (Pseudomyrmecinae). In this mutualistic interaction, plants offer different types of resources to ants like domatia (Fig. 8.3a), extrafloral nectar (see below for more details), and Beltian food bodies (Janzen 1966; Calixto et al. 2018a; Pacheco and Del-Claro 2018).

Myrmecophilous plants are non-specialized plants, which provide different food resources to ants, such as food bodies and extrafloral nectaries (EFNs; Fig. 8.3b). Food bodies are nutrient-rich structures (such as lipids, carbohydrates, and amino acids), while EFNs are glands or tissues which produce a carbohydrate-rich liquid and are not involved with pollination (Koptur 1992; Del-Claro et al. 2016; Calixto et al. 2018a; Moura et al. 2021). There are about 4000 EFN-bearing plants in the world (Weber et al. 2015), and this number keeps increasing as new plants bearing EFNs are described (e.g., Pires et al. 2017). The liquid produced by EFNs, the extrafloral nectar, is very rich in carbohydrates, but can also present different diluted compounds such as amino acids, alkaloids, enzymes, lipids, and phenols (Koptur 1994; Wäckers 2001; González-Teuber and Heil 2009). EFNs are variable in structure, morphology, and extrafloral nectar composition (Koptur 1994; Díaz-Castelazo et al. 2005; Machado et al. 2008; Lange et al. 2017), and due to this variability, they can attract a high diversity of ants and other arthropods. Some studies have shown a significant increase in spider (Nahas et al. 2016) and ant colony fitness (Byk and Del-Claro 2010; Calixto et al. 2021d) fed on extrafloral nectar. Therefore, it is expected that many other arthropods search for this nutritious reward (Koptur 2005; Nahas et al. 2012, 2016; Alves-Silva et al. 2013; Calixto et al. 2018b; Pearse et al. 2020; Moura et al. 2021).

The production of extrafloral nectar can also be impacted by insect herbivore damage, which can influence ant foraging composition and behavior (Lange et al. 2017; Raupp et al. 2020; Calixto et al. 2021a, c), ultimately influencing the local diversity. For instance, EFNs can increase the volume and sugar concentration of extrafloral nectar after simulated herbivory, attracting a higher number of ants (Ness 2003; Calixto et al. 2021c). Also, the interaction between herbivores, EFN-bearing plants, and the associated ants can be driven by environmental variables (Vilela et al. 2014, 2017; Nogueira et al. 2020; Calixto et al. 2021e), ultimately influencing the presence of other organisms, or even other mutualistic interactions, such as pollination (Assunção et al. 2014; Villamil et al. 2018, 2019; Sousa-Lopes et al. 2020). Finally, nectar concentration can lead to different patterns of ant aggressiveness, in which ants can defend the plant more effectively or not (Anjos et al. 2017; Ballarin et al. 2020; Calixto et al. 2021a), influencing the biodiversity patterns on host plants.

8.6 Perspectives

As discussed in this chapter, the J-C hypothesis has been suggested as one major force promoting diversity in both tropical and temperate forests (Comita et al. 2010; Terborgh 2012; Forrister et al. 2019). Different mechanisms might be responsible for the J-C effects, namely host-specific herbivores, pathogens, and other natural enemies. Although the number of studies focused on disentangling the drivers responsible for the J-C effects has increased recently, the role of these mechanisms in driving the J-C effects is not fully resolved. Future studies should evaluate the potential mechanisms involved in distance- and density-dependent plant survival mainly focusing on plant–herbivorous insect interactions. In addition, the extent to which density or distance dependence contributes to species coexistence and biodiversity patterns is very poorly studied (see Carson et al. 2008). Assessing the degree of their contribution to species coexistence is hard, and only few studies have assessed and/or suggested potential degrees of contribution by using the combination of empirical, theoretical, and statistical modeling approaches (e.g., Levine and HilleRisLambers 2009; Adler et al. 2010).

Considering that herbivores are one of the drivers of the J-C effects and consequently might lead to more spaces in the environment for other plant species, it is expected that the absence of herbivores would increase the abundance of seedling close to the mother plant, decreasing the species diversity. Given that, future long-term studies should attempt to test how the absence of herbivores influences the species diversity patterns in different ecosystems, with different plant growth forms, and considering the impacts on different ontogenetic stages (seeds, seedlings, and saplings). Importantly, these different studies in different regions should concomitantly evaluate how different environmental variables (e.g., precipitation, soil nutrients, temperature, latitude, altitude) are influencing the results of the plant–herbivorous insect interaction.

Although the ecosystem engineering framework can be applied to the plant–herbivorous insect interaction, there still are some topics and areas that need to be addressed and scrutinized. The impacts of ecosystem engineering from individual to community level are well known for temperate regions, but underestimated in tropical areas (Cornelissen et al. 2016; Calixto et al. 2021b). Tropical regions are hotspots of biodiversity, presenting different biotic and abiotic characteristics, and are paramount to a better understanding of how plant–herbivorous insect interactions can influence the biodiversity patterns. In addition, due to the close relationship of ecosystem engineers with the impacts on the environment and other organisms, ecosystem engineering can also be a useful tool for the study of conservation, restoration, and applied ecology. Evaluating the direct and indirect impacts that ecosystem engineers lead to the environment can help understanding the ecosystem dynamics, ultimately resulting in better conservation and restoration approaches (Boogert et al. 2006) and minimizing the impacts of climate change and human disturbances in species diversity (Calixto et al. 2021b).

Plants that provide resources can be important for attracting arthropods, representing a biodiversity enhancer. Within this view, we suggest that future studies should focus on the impacts of other mediators of the interaction between plants and natural enemies of herbivores on the local biodiversity (Bronstein 2021; Moura et al. 2021). These mediators are mainly represented by herbivores that produce a carbohydrate-rich liquid, such as hemipterans (Fig. 8.3c) and caterpillars (Fig. 8.3d). For instance, some species of Membracidae (Hemiptera) produce a liquid rich in sugar, the *honeydew*, which attracts a high diversity of ants (Way 1963; Buckley 1987; Del-Claro and Oliveira 2000; Vilela and Del-Claro 2018; Lange et al. 2019). In addition, some caterpillars are also able to produce a liquid rich in sugar that attracts many species of ants (Bächtold et al. 2013, 2017; Kaminski et al. 2013; Alves-Silva et al. 2017). Therefore, it is unclear that what are the effects of these mediators on diversity patterns and ecosystem dynamics? In sum, the rich history of plant–herbivorous insect studies has provided a sturdy foundation upon which to address additional questions related to biodiversity, restoration, and conservation.

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9 Beyond the Biophysical: Contribution of Community Forestry in Building Social-Ecological Resilience

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Abstract

People's engagement in forestry has been a key strategy to sustainably manage forests. While such approaches have proven effective in protecting and restoring forests, emerging evidence shows that they go much further in enhancing the resilience of local communities against shocks and stresses, ultimately sustaining forest resources. Sporadic evidence reports community forestry's (CF) support to local communities in dealing with climate impacts as well as disasters. This article reviews the multiple roles of CF in different contexts, through case studies done in Cambodia, Myanmar, Nepal, and Viet Nam in tackling climate impacts and COVID-19 restrictions. The article provides an illustration of key contributions from CF in addressing sources of vulnerability of forest-dependent communities and points out potential improvements in the CF programs. In doing so, it adapts Ostrom's Social-Ecological Sustainability framework. The article presents conclusive evidence that CF has the potential to help improve the resilience of social-ecological systems. However, the results are not optimal,

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and performance varies greatly across social, ecological, political, institutional, and livelihood contexts. We argue that with stronger integration to larger systems of multi-level and nested governance, the CF has potential to deliver more benefits to resilience building, climate adaptation, and disaster preparedness. This is complemented by integrating CF programs in climate adaptation and disaster-related policies and plans and providing capacity and resource support for on-the-ground actions under the leadership of local communities.

Keywords

Community forestry · Social-ecological system · COVID-19 · Resilience

9.1 Introduction

Nearly a third of global forests are managed with the participation of local communities (FAO 2015). Local communities have strong cultural, social, and economic connections to forests. Acknowledging this, in the last four decades, many governments have formalized local communities' relationships with forests through community forestry (CF) programs primarily to protect forests, tackle deforestation, and restore forests (Gilmour 2016). Different forest management regimes, employing the CF approach, recognize different modalities of local communities' rights to use and manage forests, and also tasking with a number of forest protection and management responsibilities within the purview of these management modalities (RECOFTC 2013).

Overwhelming evidence shows that CF, when supported with an enabling environment, delivers in achieving the objectives of forest conservation and restoration, one of the primary objectives of introducing the CF programs in many countries (Niraula et al. 2013; Gilmour 2016; Luintel et al. 2018). Further evidence shows that community forestry goes much beyond in delivering on other fronts such as livelihood improvement of local communities, gender equality, and social inclusion (Giri and Darnhofer 2010; Sapkota et al. 2019). Contributions of CF on social and economic fronts are necessary for the survival of forest resources, which requires tackling root causes of forest loss and enhancing the resilience of ecosystem and forest-dependent communities (Sapkota et al. 2020). The resilience of forest-dependent communities against interlinked shocks from climate impacts, disasters, and unsustainable developments is critical amid their increasing intensity and severity and resulting harms to ecosystems and community members (Ofoegbu et al. 2017). It is in the context that climate change is projected to get worse in the absence of drastic actions to curb climate change and unsustainable development (Jia et al. 2019).

While a number of studies have reported positive contributions of CF in improving biophysical characteristics of forests and providing livelihood benefits to local communities, scholarly knowledge remains limited on CF's contributions to enhancing resilience (Gilmour 2016). While it has been generally accepted that CF can contribute to enhancing resilience, lack of adequate understanding limits the promotion of such aspects in CF programs. In such a context, this article attempts to answer "how can community forestry enhance the resilience of forest-dependent communities' against shocks (e.g., disaster, pandemic or climate impacts) and what factors contribute to enhancing resilience and what improvements are required for their effective roles?".

Based on four case studies of community forestry in varied contexts, this article shows that CF positively contributes to enhancing the resilience of local communities. However, the CF's contribution greatly varies due to a number of factors, such as supportive policy and regulatory environment, integration of CF with other government programs, including climate adaptation and disaster mitigation, and capacity and resource support to local communities. In this article, we argue that CF has a strong potential to enhance community resilience and should be fully tapped by providing an enabling environment.

9.1.1 Social-Ecological Resilience in Community Forestry Context: A Conceptual Framework

Community forestry includes "initiatives, science, policies, institutions and processes that are intended to increase the role of local people in governing and managing forest resources" (RECOFTC 2013). A community forest can be considered a social-ecological system (SES) composed of multiple subsystems of (1) forest, which can be subdivided into different forest types based on composition and productivity, (2) resource units such as trees, herbs, water, soil types, wildlife, (3) users or local communities, who can be divided into different subgroups according to their location, ethnicity, livelihood source, wealth status, and (4) governance system, comprising of rules and different bodies such as community forest user groups (CFUG), and community forest management committees (CFMC) that help govern the community forest (Ostrom 2009).

The subsystems of a community forest interact to produce outcomes such as sustainable management of forest resources. In addition to biophysical interactions among the elements of forest and resource unit subsystems, the interactions within and across the subsystems, for example, among the users are self-organization, deliberation, information sharing, decision-making, networking, protection of forest, and harvest of forest products. Similarly, the outcomes from such interactions can be social (equity, inclusion, trust among community members), economic (income, secure livelihood) and ecological (increased growing stock and biodiversity, sustainable harvest) (Ostrom 2009). Those outcomes include the capacity of the SES to endure disturbances such as climate extremes, pandemics, and disasters to subsystems retaining the essential structures and functions and continue to develop and innovate (Tidball et al. 2018).

A community forest in a community-based natural resources management regime is a grassroots level cross-scale regime, involving a wide range of non-local actors influencing interactions in a SES through a variety of ways such as channels of expanding market, regulatory regimes, and complex political negotiations and a larger set of discourses (Ojha et al. 2016). In such a context, social, economic, and political settings, related ecosystems as well as interactions within and across the subsystems, influence the resiliency of the social-ecological system positively or negatively (Ostrom 2009; Cinner and Barnes 2019). Their outcome has a positive relationship with the resilience, meaning the positive results such as improved forest conditions and strong trust among community members (users) contribute to making more resilient SES, enabling production of more products and services (Cretney 2016).

CF is practiced in forest landscapes with a predominance of agrarian livelihoods, which are highly sensitive to climate events and disasters. Dependency on natural resources such as forests and water, which are very sensitive to changes, for example, on hydrological and atmospheric systems, contributes to high vulnerability of resource systems and users, making the entire social-ecological system vulnerable to human-induced climate change (Pandey et al. 2015; Ofoegbu et al. 2017).

In defining the resilience concept, we consider social-ecological system resilience to be more holistic compared with engineering and ecological resilience and view humans as integral to the ecosystem, and their actions play critical roles to respond, cope, and adapt to change (Berkes and Ross 2013; Magis 2010; Nikinmaa et al. 2020). The SES resilience concept extends beyond basic resilience (or bouncing back to a similar state) to include adaptive and transformative resilience, making necessary changes to social-ecological systems (Cretney 2016). Hence, resilience is a dynamic concept and is multidimensional in nature, comprising social, economic, and ecological aspects. The resilience requires self-organization of the system as well as consideration of agency, conflict, and power of the users (Bhattarai 2020).

Some of the commonly used indicators of social-ecological system are socioeconomic diversity, biodiversity, stock of natural resources, knowledge, skills, employment, ecosystem services, income, access to resources, participation of community organizations, education, among others (Nikinmaa et al. 2020).

9.2 Methodology

9.2.1 Community Forestry in the Selected Countries

A community forest each in Cambodia, Myanmar, Nepal, and Viet Nam was purposely selected to provide an illustration of CF in different (social, cultural, policy, economic, environmental) contexts. As multiple CF programs are practiced in the study countries, attributes of the community forestry user groups (CFUGs)[1] vary within and across the countries. Their attributes are influenced by multiple factors: CF processes and the bundle of rights and responsibilities conferred to them

[1] A group of households in one or more villages managing forests as community forests. The user groups have different names across the countries. They are registered with relevant government authorities, and each of them has a leadership body, often called CF committee, for operational decision-making.

Table 9.1 Overview of community forestry program in four countries in the Asia–Pacific region

Country	Community Forestry models	Legal instruments on CF	CF coverage (number of communities, forest area, and families)
Cambodia	Community Forestry, community protected area	2002 Forestry Law, 2003 Sub decree on Community Forestry Management;2006 Prakas (declaration) on Community Forestry Establishment Guideline	636 community forests, 516,812 ha; 168,248 families (2018) (Data source: unpublished data from Forestry Administration, Cambodia) 174 Community Protected Areas; 296,511 ha; and 46,121 households (2020) (Data source: DCL 2020)
Myanmar	Community forestry	Community Forestry Instructions, 1995 (revisions 2016, 2019) Community Forestry Strategic Plan (2017–2020)	6366 community forests, approximately 347,404 ha; and 161,696 households (2020) (Data source: unpublished data from Forest Department, Myanmar)
Nepal	Community forest (in and outside protected areas), leasehold forest, collaborative forest, community forest, religious forest	Forest Act 2019; Community Forestry Development Guidelines 2002 (third revision 2015)	22,266 Community forests, 2.31 million ha, and 8.1 million people (2020) (Data source: unpublished data from Federation of Community Forestry Users Nepal)
Viet Nam	Community forestry management	Law on Forestry 2017; Decree 156/ND-CP 2018	More than 10,000 community forests, 1.16 million ha (2018) (Data source: unpublished data from Ministry of Agriculture, Forestry and Fisheries, Cambodia)

by policy and regulatory frameworks, local livelihood contexts, size of the CFUGs, and status of natural resources (Gilmour 2016). Similarly, they are at different stages in the implementation of CF programs (Table 9.1).

9.2.2 Data Collection and Analysis

In each of the four countries, a community forest was purposively selected for the study (Table 9.2). Case study approach was followed, and qualitative and quantitative data such as attributes of community forests and user groups, governance, and

Table 9.2 Basic information of selected community forests

Country	Name of community forests	Members (households)	Community forest area (ha)	Year of CF establishment	General livelihoods
Cambodia	SamakyTrapeang Totim	322	439	2016	Main: rice and vegetable farming subsidiary: gold mine exploration (for some)
Myanmar	Heinze	24	57	2017	Home gardens growing rubber, cashew nut, and betel nut
Nepal	Bishnupur	63	3.8	2005	Sugarcane, vegetable cultivation
Viet Nam	Muong Phu	235	2337.5	2010	Agriculture and forestry production

CFUGs' and CFMCs' response to help their vulnerable members during crises were collected from each of the community forests at two different times. For three sites, those in Cambodia, Thailand, and Viet Nam, data were collected during the early stage of the COVID-19 pandemic (between December 2020 and January 2021) and access to communities to researchers, which also influenced the selection of communities. Data for Nepal's site were collected in the beginning of 2020.

In each of the communities, co-authors led data collection and analysis, employing tools such as group discussions, key informant surveys, with CFUG leaders, elderly members of the communities, local government representatives (e.g., commune councilor), and forest officials such as from Forestry Administration in Cambodia, who have the mandate to support and oversee CFUGs. Similarly, focus group discussions (at least two per community) were conducted with CFUG members and with women and the poor in each of the communities to understand whether and how they benefitted from community forest when they experienced shocks.

Based on the field data collection and consultations with different stakeholders, a case study was developed for each of the CFUG. Each of the case studies was treated as a social-ecological system and included social, cultural, political, economic, environmental contexts of the selected CF. Finally, each of the cases was analyzed in terms of its institutional, social, economic, and ecological resilience, using the social-ecological system framework of Ostrom (2009) and Burton (2015) in analyzing community resilience to natural hazards and disasters.

9.3 Case Studies

9.3.1 Community Forestry and Livelihood in Samaky Trapeang Totim Community during COVID Pandemic in Cambodia

9.3.1.1 Samaky Trapeang Totim Community and Community Forest

Samaky Trapeang Totim Community Forest, located in Romtom commune, Rovieng district, Preah Vihear province of Cambodia, has 322 families (1456 people/706 women) as community forest members. Majority of the CFUG members are Kouy indigenous people, while approximately 30% are migrants from other places. Cultivation of rice and vegetable crops is the main occupation for the members, while some members also work in gold mine exploration and agribusiness for their livelihood. Community forest resources are important for the livelihoods and cultural values for this community. Community forest helps maintain their spirits in the forest so that members can come together for traditional ceremonies, a common practice among Kouy indigenous people.

The CFUG members of Trapeang Totim conducted participatory wealth ranking of their community members, dividing themselves into four categories for equitable benefit sharing. The better-off group, characterized by a family possessing land larger than 3 ha, up to 50 cows and agriculture machinery, comprises 30% of

322 households. Similarly, the medium group, characterized by a family possessing land between 2 to 3 ha and four to five cows, comprises 55% of households. Besides agriculture, they sell labor and gather forest products for consumption and selling. They are the people who are mostly involved in forest protection and management. The poor and very poor group, characterized by landless families or those who own small land parcels, lack a labor force due to the prevalence of widow and/or old age people in their family, comprising 15% of households. They depend substantially on forest resources, particularly when they do not have income from other sources.

The community forest covers 439 ha of deciduous forest. The community had a formal agreement for this community forest in 2016, providing secure tenure over the forest for 15 years. A 15-member (9 women) Community Forestry Management Committee (CFMC) provides leadership to the CFUG. The CFMCs have a role in the overall management of the forest, engage with stakeholders to receive support to manage their forest, and solve the conflict as there are still conflicts with villagers who have land inside the community forest. They ensure that women are involved in all the community forest management activities, though it is not easy for women to join the CFUG meetings, which usually take place far from the village.

Regarding CF activities, the CFUG members participate in forest patrol. They do so with the understanding that improving the community forest's quality would benefit everyone in the village. On the institutional side, the CF management committee and key members have knowledge and skills on office management such as file management, record keeping, financial management, and accounting. Similarly, the CFMC members and CFUG members have knowledge on the CF management planning process, including CF credit formulation. They have a functional CF credit scheme[2] benefitting 33 members, of whom 24 are women. With CF credit, members can borrow money to invest in their agriculture or to use for urgent situations, while the CF is also able to generate income for the management of forest, particularly for forest patrolling. Through the scheme, they access finance more easily than from the other microfinance schemes due to the simple process and no requirement of collateral and, in turn, help implementation of community forest management plan.

Regarding the contribution of the CF, local community members report that women's participation in decision-making and implementation of the decisions on the management of forest has increased. Community forest resources, including non-timber forest products, are well maintained through regular patrolling that allow for CFUG members, especially the poor families, to collect, consume in-house, and sell for their livelihood. The community reported that the number of illegal logging and land encroachment is lower than before the community forest was established in 2016. Local communities also report forest regrowth and

[2]Community forest credit scheme is a community managed mechanism to self-sustain source of income for forest patrolling and management. It provides financial resources to community members to invest in their landscape. The scheme was introduced in 2015 and expanded to 21 communities until 2019 and is growing.

restoration of degraded areas due to better management under CF. Similarly, CFUG members think that their relationship with the government, particularly the Forestry Administration of the Royal Government of Cambodia, and non-government organizations that are supporting them, such as RECOFTC,[3] a non-governmental organization supporting CF in the Asia–Pacific region, have substantially improved through community forestry.

9.3.1.2 COVID-19 and Role of Samaky Trapeang Totim Community Forest

Until the end of 2020, when the data were collected from the community, there were no COVID-19-positive cases in Samaky Trapeang Totim. However, CFUG members are impacted indirectly such as by their family members living in cities losing jobs and reducing income from the sale of agricultural products by at least 30% due to COVID-19-related restrictions and the resulting dip in demand. For instance, the price of fresh cashew nuts produced by CF members on their private land dropped from 5000 Cambodian Riel[4] to 3000 Riel per kilogram and rice from 1200 Riel to 900 Cambodian Riel per kilogram. The local community members were also concerned about the spread of COVID-19 as well as inability to continue their children's study. For example, a family whose only earning member lost her job in Phnom Penh, the capital city of Cambodia, due to COVID-19 lost their only source of income and had to find ways to manage added expenses due to the additional members returning to the house. They also had to prioritize expenditure in the family, for example, by using less water (for washing) because they need to buy water.

To overcome such situations, the family used the community forest in multiple ways. They harvested vegetables (such as bamboo shoots, mushrooms, and different herbs) from their community forest. They borrowed money from the CF credit to buy food. People who reported using those products belonged to the poor and medium-income group, who accounted for around 70% of villagers. Similarly, from CF credit, each member borrowed up to 500,000 Riel. However, because of the limitation of capital in the CF credit, only 10–12 families could borrow at a time. As a result, members take turns to borrow money from the CF Credit scheme.

Other supports to CFUG members include information from their committee members to stay safe from COVID-19. The information was critical considering there was little known about COVID-19 in the early stage of the pandemic, and local community members did not have a direct channel to receive reliable information on how to prevent spread of the virus and what to do if anyone is infected. The CFMC members received such information from authorities and disseminated to their CFUG members.

[3] Regional Community Forestry Training Center for Asia and the Pacific.

[4] Approximately 1 USD = 4000 Cambodian riel.

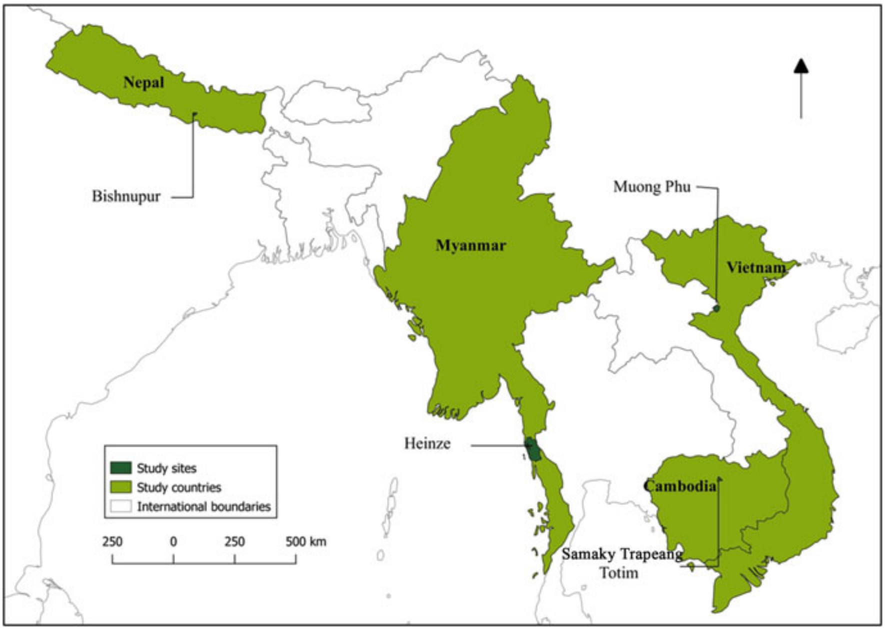

Fig. 9.1 Map showing study sites located in four different countries

9.3.2 Community Forestry and Livelihoods During COVID-19 Pandemic in Heinze Village, Myanmar

9.3.2.1 Heinze Community Forest

Heinze village is located in Ye Phyu Township of Dawei District in Tanintharyi Region of Myanmar (see Fig. 9.1). It has 53 households comprising 457 people (223 male and 234 female). The majority of the people in the Heinze village are Dawei ethnic group, and others belong to Mon and Karen ethnic minority groups. Villagers representing 48 households in the village rely on the water resources from the forests. The forest is tropical evergreen and has a dense stock of primarily *Dipterocarpus macrocarpus*, *Xylia dolabriformis*, *Eugenia jambolana*, *Dillenia ornata*, *Erythrina suberosa,* and *Swintonia schwenckii*.

The main livelihood for the villagers is home gardening (rubber, cashew nut, and betel nut). Hence, their major asset is land. According to the participatory wealth ranking conducted by the Heinze community members, high-income households own 10–15 acres of orchard, moderate-income group has 5–10 acres of land, and low-income group (poor) has 1–5 acres of land. There are ten high-income households, 20 moderate-income households, and 23 low-income (poor) households in the village.

Out of 53 households, 24 households in the village have formed the Heinze Community Forest User Group (CFUG) to manage a forest area of 140 acres (approximately 57 ha). Their forest is dense and is of tropical evergreen type. To manage the CF, a Community Forest Certificate (CFC) was awarded to the CFUG in 2017 by the Myanmar Forest Department. The CFUG has five CFMC members, including one female member, which meets quarterly to discuss the CF activities. They possess facilitation skills to run the meetings and resolve forest-related conflicts in their community.

CFUG remains engaged in a number of activities to protect and improve the forest and develop the community. The CFUG members are united to protect forests from illegal loggers and forest fires. For example, in December 2020, the villagers faced illegal logging near and around the CF. As soon as they knew about it, they reported it to the local Township Forest Department Office for help to tackle the issue. They keep records of their financial transactions and in the book for which CFMC team possess skills of book keeping ensuring transparency of CFUG transactions.

Regarding the achievement of the CFUG, because of their patrolling and forest protection activities, they were reportedly able to reduce 95% of illegal activities in forest (particularly illegal logging) after the handover of forest to them. Similarly, they have been doing gap planting or enrichment planting every year, receiving seedlings from the Forest department. They have established five acres of tree plantation in the forest with a survival rate of 95%. Contributed by such activities, the condition of their forest improved noticeably with 35% more regeneration of the valuable trees such as *Xylia dolabriformis* (Iron wood) and *Dipterocarpus tuberculatus* in the forest.

CFUG harvested and donated 6 tons of timber for constructing a local monastery. The CFUG also has been operating a revolving fund of around eight million Myanmar Kyat[5] or 4500 USD, which was contributed to CFUG as seed money by a CF project to provide financial access to its members. Using the money from the fund, CFUG members have bought a lawn mower to clean grasses in the home gardens and in the construction of fire-breaks in the community forest area. The owners of big home gardens hire the lawn mower for cleaning the gardens. Contribution by labor and lawn-mowers provides them a higher income than only labor contribution. The profit from interest of loans from individual members is used by the CFUG in protecting the forest, such as through forest patrolling, planting, fire break making, and attending meetings held by relevant organizations.

The community forest provides non-timber forest products (NTFPs) for the livelihood of the community. The establishment of the community forest has offered more benefits not only to CFUG members but also to non-CFUG members who get water from the community forest for household use and irrigation. For that reason, they have received irrigation system support from Tanintharyi Nature Reserve Project. Similarly, the Rural Development Department financed the installation of an irrigation system in the village.

The CFUG also reported on improved relationships with government organizations such as the Forest Department and non-governmental organizations

[5] 1 USD = approximately 1850 Myanmar Kyat.

such as True Friends, Swiss Programme for Research on Global Issues for Development (R4D) and RECOFTC.

9.3.2.2 Community Forestry and COVID-19 Restrictions in 2020

When the local community faced restrictions introduced by the government to curb the spread of COVID-19 in 2020, forest products such as dog fruit (*Archidendron pauciflorum*) helped local community members, particularly the poor, to continue their livelihood (household consumption). They could not sell the product due to travel restrictions, making it difficult to send to market and lack of buyers during the pandemic. Similarly, the monastery, which was built from the timber contributed by CFUG, was used by elderly people for social exchanges and also for community affairs such as meetings and awareness-raising about COVID-19.

CFUG, especially the CFMC team, used different coordination channels like CF networks to get COVID-19 preventive materials (Hand Gels and Masks) from charitable/development organizations during the pandemic. Around 20 elderly people in the village received financial support (800,000 Myanmar Kyat or MMK, approximately 600 USD) from R4D through CFUG. The revolving fund also assisted the CFUG members in keeping existing livelihoods. All CFUG members (24 households) received loans from the revolving fund, at an average of 200,000–250,000 Myanmar Kyat for each household, which is roughly (140–180 USD per household). In addition, a water reservoir was constructed with the financial support of a development organization. Through coordination of the community forest network chairman, the CFUG received hand gels, masks, COVID-19 awareness posters, and equipment support such as Jungle boot, sleeping bed, knife, lawn mower for patrolling in CF during the pandemic.

The CFMC provided strong leadership and coordination to help CFUG members at the time of COVID-19 restrictions. The CFMC was able to coordinate with the village authorities in sharing information about COVID-19 in the community and distributing hand sanitizer and masks to 48 households who were in the village during the pandemic, supported by RECOFTC to tackle the COVID-19 pandemic in the community.

9.3.3 Community Forestry and Climate Adaptation in Bishnupur Village, Nepal

9.3.3.1 Bishnupur Community and Community Forestry

Bishnupur all women CFUG, located along the Harion River of Harion Municipality ward no. 7 in Sarlahi District of Nepal, comprises 63 households. The ethnic composition of the Bishnupur community has Brahmin and Chhetri (76%), indigenous ethnic groups such as Kirat (22%), and Dalits (2%). The main source of livelihood of the local villagers is sugarcane cultivation. In the last five years, villagers have also started cultivating vegetables for commercial purposes.

Among the total population of 359 persons, 70.46% are literate, and about half of them have completed at least high school level of education. The percentage of poor households in Bishnupur is just above the national average of 25.2% living under the poverty line. Bishnupur village and their forest are situated at the bed of Chure[6] and Bhabar[7] regions. About a kilometer stretch of Harion River flows along their forest, settlement, and farm lands and causes flash floods.

9.3.3.2 Bishnupur Community Forest and Climate Vulnerability

All the households of Bishnupur formed a CFUG and registered at the District Forest Office (currently known as Division Forest Office) in 2005. The leadership body, the community forest executive committee, is composed of all women since its formation. Bishnupur CFUG is managing a forest of 3.8 ha, which is located above the village and agricultural land (more than 42 ha) along with the Harion River, and hence, it is highly important as a shield from floods and strong wind.

Located at the foothills of the Chure mountain range, the Bishnupur area is highly vulnerable to flash floods due to broken and soil eroded Chure topography caused by increased amount and intensity of rainfall by almost 20% in the last 30 years. Fragile Chure in the upstream area and loss of topsoil by intense rainfall pose flood and landslide risks, threatening lives, water supplies, and basic infrastructure downstream of the river. The major impacts of climate change recorded during a vulnerability assessment conducted by the community in 2014 and field assessment in 2020 showed that the community is vulnerable to severe floods, which occur every 20 years, depositing silt and debris up to 500 m in the agriculture fields, costing on an average 40,000 USD to rebuild the agriculture land (de-siltation, fertilization, and crop damage considered) and make it fit for cultivation. On average, 0.5 m of river-bank is eroded annually by floods resulting in an increased cost to protect farmland along the river-bank.

Increased occurrence of pest and disease to agriculture crop and mosquito-borne and water-borne disease to human and livestock added to the cost of healthcare of all (human, livestock, and farmland). Similarly, the community reported number of flooding days reduced the movement of people by 15–20 days annually, affecting the schooling of children, reduced employment opportunities for the poor, and delayed agriculture works.

Extreme heat and cold events increased diseases to low-income families resulting in increased spending for healthcare, making them further poor. Participation of low-income families in social events has reduced as their priorities remain to earn enough to survive on a daily basis. Vulnerabilities of the poor, especially women, elder, differently-abled people, and children, have been increased.

[6]The Chure range (also called Siwaliks) rises steeply from the Terai plains along the whole of its northern border. It is extended as a contiguous landscape from east to west in 33 districts. This is the first and lowest ridges of the Himalayan mountain system. These are a series of low hogback ridges, in a sinuous pattern that cross the length of Nepal.

[7]Bhabar is the gently sloping coarse alluvial zone below the Siwalik Hills (outermost foothills of the Himalayas) where streams disappear into permeable sediments. The underground water level is deep in this region and then rises to the surface in the Terai below where coarse alluvium gives way to less permeable silt and clay.

To reduce the damage from flash floods and resultant soil erosion, local communities planted an area of 3.8 ha with indigenous tree species such as Sissoo (*Dalbergia sissoo*) and Khair (*Acacia catechu*) and exotic species such as *Eucalyptus spp*. to rehabilitate the flood eroded land and to protect the village from flooding risks. However, erosion of river bed continued, and threats posed by flood continued to exist. Through collective assessment and decision-making, they undertook the following activities in 2015–2017 for Harion River Bank stabilization to protect from flood-related risks.

- A total of 150 m of bamboo weaved meshed with live bamboo posts erected along the river bend supported by sandbags retaining walls.
- Plantation of 200 bamboo rhizomes and 2000 grass slips along 1-km stretch of the river.
- 50-m-long loose stone gabion wall with improved design to protect high current bends where other options do not work.
- Plantation of grafted seedlings: 252 mango and lychee for income diversification.

The CFUG received support from the key stakeholders in implementing those activities. For example, District Soil Conservation Office and District Forest Office provided technical and material support to build a loose stone wall, bamboo weaved meshed with live bamboo posts, and bamboo plantation along the river bank. RECOFTC provided financial support of 6500 USD to cover the cost of wire, empty cement bags, stone transportation, and skilled labor cost. Likewise, the Regional Horticulture Development Office provided mango and lychee planting stocks at subsidized rates. In all those activities, the Bishnupur community contributed manual labor, and bamboo culms and rhizomes for plantation.

The implementation of aforementioned measures reportedly resulted in reduced losses from siltation and debris in more than 45 ha of land (settlement, farmland, and forest), which saved an estimated USD 500/ha, as shown by a monetary analysis of the climate impacts and benefits of nature-based solutions jointly conducted by RECOFTC and Practical Action in 2020. Similarly, it saved potential crop damage worth 16,000 USD from devastating floods, which occurred every 20 years. They also reduced the threat of damage to property and infrastructure, reducing the cost of riverbank protection by individual farmers.

These measures have reduced river-bank erosion (average annually 0.5 to the stretch of 500 m) for the last 4 years, and there is no deposition of debris in the village. Likewise, greenery in the riverbank throughout the year is maintained, further helping to reduce the soil erosion.

In terms of indirect benefits, the availability of grasses to feed cattle increased. The community expects to receive at least 50 USD annually from the sale of bamboo poles after 3 years. Mango and lychee are expected to start giving financial returns in the next 3 years. Similarly, downstream riverbanks and lands were saved due to reduced water current in the river. More carbon sequestration as bamboo is a fast-growing species is reported as a key environmental benefit from the measures.

These actual and perceived benefits have alleviated the most vulnerable—poor and Dalits' fear of flash floods and their adverse implications to their daily income. More importantly, the success in those activities strengthened the leadership capacity of CFMC members and inspired other women to take the lead of CFUG and other such community-based groups in tackling issues affecting women the most. For example, a nearby Pragatishil CFUG in Harion Municipality followed the same approach to enhance climate vulnerability.

9.3.4 Community Forestry, Payment for Forest Environmental Services, and COVID-19 in Viet Nam

9.3.4.1 Muong Phu Community and Community Forest

The Muong Phu community, located in Thong Thu commune, Que Phong district, Nghe An province of Viet Nam, has 235 households, mainly belonging to the Thai ethnic group. Located far from cities, the community has limited infrastructure and economic opportunities. The main livelihood of the local people is agriculture and forest-based activities such as harvesting and selling non-timber forest products, such as honey and timber from planted forests.

In 2010, the Muong Phu community forest was established to manage 2337.5 ha of natural forest, as there was a ban on the harvest of forest products by the government, resulting in limited income opportunities for the local community members from the forest. The forest area managed by the Muong Phu community plays an important role in protecting water resources and ecological diversity of the forest. This area is an important watershed and contributes water resources to the Chu River. This forest area is classified as a protection forest and special-use forest (part of the area is in Pu Hoat Nature Reserve, which belongs to Western Nghe An Biosphere Reserve).

Muong Phu community forest has a management committee (CFMC) comprising of village header, Forest Protection team, Reconciliation team, Fund keeper, and other members. CFMC members disseminate policies of government to community members. They discuss among themselves on how to organize patrolling and use the CFUG fund. The immediate benefits of establishing a community forest are the responsibility of the local people linked to the enhanced forest resources they manage.

Before 2016, local people used to harvest and sell forest products. In 2010, when Muong Phu community forest was established, they focused on forest protection and the implementation of development policies. Because of the relatively large forest area and a small number of households, Muong Phu community established 12 forest protection groups (6–8 people each), including men and women, to conduct forest patrol and protection groups (dry season 3 times/month, rainy season 1 time/month). The forest protection team's expenses (payment to community members at the rate of about 200,000 Viet Nam Dong (VND)/day or approximately 9 USD/day for its operations and patrol are covered from the community fund, which is a small source of revenue for people involved in forest protection. The efforts of community members have helped significantly to improve the forest quality in this area with increased coverage and increased supply of non-timber forest products such as bamboo shoots, yellow flower tea, honey, and medicinal herbs.

9.3.4.2 Community Forestry and Payment for Environmental Services (PFES)

After 2017, Muong Phu CFUG received forest protection support money 1,045,660,000 VND (US$45,350) from the government under the payment for forest environmental services (PFES) scheme in Nghe An province. From that money, the community spends 30 million VND (approximately 1300 USD) every year on forest patrol and protection activities, with the remainder divided by five million VND (approximately 217 USD) per family. It is an important source of support for the community. In addition to the payment for forest environmental services, Muong Phu CF is also entitled to the policy of Decree 75 on the mechanism and policy of forest development associated with sustainable and rapid poverty reduction and assistance to ethnic minorities. Pu Hoat Nature Reserve allocates a part of the forest area to the community for protection; they received payment for 1784.2 ha at the rate of 400,000 VND/ha (approximately 17 USD/ha) in a year.

Therefore, the Muong Phu CFUG fund is stable; CFUG members have contributed the money they received under PFES and Decree 75 to the fund to build a new cultural house, upgrade, and repair the village access road and canal system to increase agricultural production. Although the CF does not have funds to provide loans to its members, Viet Nam Bank for social policies provides loans for local companies or individuals. However, people in Muong PhuCFUG have not shown interest in starting a business so far (they do not have any business plan to get a loan).

Similarly, there was a tendency among people to expand their cultivated lands to forests, due to lack of clear boundaries resulting from difficulty in boundary delineation in mountainous areas. Such actions would lead to frequent conflicts between households and Pu Hoat Nature Reserve. These disputes used to be mediated by the village head, commune staff, and forest rangers. However, after establishing the community forest and empowering communities to manage forests, the CFMC members started playing such roles of mediating to mitigate conflict. This promoted a sense of mutual protection among households in the community. The forest land disputes have also declined significantly (they do not have any cases of forest land disputes after 2018).

Since 2017, when the policy of payment for forest environmental services to the Muong Phu community was implemented, women’s participation in training and raising policy awareness increased. They also join in forest patrol and protection in the community. Before that, women mainly participated in activities to support animal husbandry and agricultural production. The payment from the government is very critical for local livelihood, particularly because the agricultural productivity is low in Muong Phu because of its location in the high mountain.

In addition, the benefits received from the community forest include honey, yellow flower tea, bamboo shoots, and medicinal herbs. Before 2017, people from neighboring areas used to come to collect non-timber forest products from Muong Phu CF. However, after the local community was assigned to responsibilities to manage the community forest, the NTFPs are harvested by Muong Phu CFUG members only.

The elderly members of the CFUG have traditional/indigenous knowledge of protecting forests, which they pass on to family and community members. It is their experience, which is used in identifying herbs and understanding the forest's topography, thus significantly supporting forest patrol by rangers and CFUG members.

Community members are trained by commune officials and forest rangers to implement forest policies on forest protection and development, harvesting of non-timber forest products, and prevention of forest fires (two to three times a year). Before 2017, people used to illegally harvest forest products. After the policy of "closing the forest" was informed to community members, the illegal harvest significantly reduced, mainly those by people coming from neighboring areas.

9.3.4.3 COVID-19 Impact and CF's Contribution

During the early stage of the pandemic, which was around February and March 2020 and peak period of COVID-19 in Viet Nam around August 2020, the government carried out social isolation and restricted crowds. COVID-19's information was announced on loudspeakers in each village. Besides, commune officials and village leaders, who also led the CFMC, regularly informed each household, reminding them of the implementation of disease prevention practices during this period.

The impact of COVID-19 affected all aspects of the socio-economy, with more impacts to people working in urban areas. The government's anti-pandemic policies were considered effective, and the implementation of such policies was supported by leaders of the community forest in the community.

The community of Muong Phu village was also affected by COVID-19 restrictions. Their business activities, agroforestry production, were halted, directly affecting their livelihoods. Workers returning to their hometowns from urban areas also exerted socioeconomic pressures on their family members and the local governments. First, before returning to the community, they had to be isolated at the local health facilities. Human resources were required to ensure effective isolation. Secondly, the workers returned from epidemic areas to their localities, causing anxiety and fear of epidemic outbreaks in the community. Third, after the isolation, several people returned to their localities without any work, and engage in eating and drinking gatherings, causing insecurity in the locality.

Besides, the community took specific actions in implementing COVID-19 epidemic prevention, such as mobilizing the forest patrol team also to enforce restrictions and check the implementation of social distancing measures. They divided inspectors at the routes into the village and banned the entry of people coming from elsewhere and distributed masks and hand sanitizers for free to all people in the community. The costs for this were covered by the community using the CFUG fund. In a short time, the CF contributed human resources and some financial resources to prevent the spread of COVID-19 in the community.

9.4 A Synthesis and Discussions

The synthesis of the four cases shows that community forestry is applicable in a wide-ranging context. As explained in four cases above, CF worked well in the communities with households ranging from 24 (Heinze CFUG) to 322 (Samaky Trapeang Totim CFUG) and forest area ranging from 3.8 ha (Bishnupur CFUG) to 2337.5 ha (Muong Phu CFUG). Likewise, it is evident that in addition to protecting and restoring forests, community forests offer multiple benefits, such as an increased and sustained supply of timber, non-timber forest products, water; protection from climate hazards; and income for local communities. More importantly, CF contributes to enhancing social-ecological resilience in forest landscapes, going beyond biophysical improvements. It is in the context that CF programs are also at different stages across the study countries, indicated by less than 1000 communities in Cambodia to more than 22,000 communities in Nepal under CF programs (Table 9.1). Following is the major outcome contributing to the resilience of social-ecological system:

9.4.1 A Community-Level Institutions to Systematize Interactions

Community forestry provides locally-led and inclusive institutions to help manage forest resources and community development. In all the cases, they have a defined set of households and collectively set rules to bind them to protect, restore, or manage specified areas of forests. Similarly, all the community groups had a leadership body to facilitate engagement among community members for forest management activities such as patrolling, forest plantations, sustainable harvesting practices, as well as access CFUG fund (known as revolving funds or CF credits) to their members during their need. In doing so, CFUGs employed participatory approaches to ensure space and voice for all the resource users is heard and thus minimize conflict incidences and mediate conflict when needed.

In regard to gender inclusion, a global issue affecting women, particularly in rural areas in the global south, community forestry provides women with the platform for social change, as was evident in Bishnupur in Nepal and in Samaky Trapeang Totim CF in Cambodia. Social change from women leadership is facilitated by explicit inclusive provisions in CF program and policy, such as at least 50% of positions in community forest management committee, including the chairperson and secretary level—to women in Nepal's community forestry program (DoF 2009). Such provisions in CF programs are critical to ensure that resources and benefits of communal resources are not used to bolster inequality and provide voice to marginalized groups, including women in negotiations, helping to redefine their social roles and rights and influencing the decisions and benefit-sharing, as highlighted by Lin et al. (2019) in her research in Myanmar. In doing so, CF provides such marginalized groups agency to change underlying social norms that discriminate against them (Giri and Darnhofer 2010).

Similarly, at the time of crises, whether climate hazards such as in Bishnupur or COVID-19 restrictions, reported in other three communities, the community leaderships, precisely CFMCs, worked with government agencies to gather information and provide safety kits and relief material to support their community members during the lockdown situation. This role of the leadership is critical to ensure that the support reaches needy households in time. Improved network with government and non-government agencies in all countries enabled them to access information and material support to tackle climate impacts, for example, by addressing water-related issues in Bishnupur, and Heinze and COVID-19 restrictions in Samaky Trapeang Totim, Heinze, and Muong Phu communities.

The CF's strong role in responding to natural disasters or crises is also supported by CFUG being first responders when Nepal was hit by a disastrous earthquake in 2015 who provided shelter and relief materials and timber for reconstruction to their community members (Gentle et al. 2020). Such actions suggest that a community-level strong institution is a key to the resilience of any community against disaster and crises. The important roles such local-level institutions play is referred to as institutional resilience by Burton (2015). Such roles are facilitated by the participatory approach that CF programs promote. For example, the participatory tools such as participatory wealth ranking that most of the CFUGs employed help overcome data gaps to identify and target vulnerable households (Gentle et al. 2020). In conformity with literature, local communities used such information to collectively decide the use of CF resources (e.g., fund) to tackle a key source of vulnerabilities, inadequate livelihood for the poor in all four communities, and climate impacts such as drought and floods in Bishnupur. Such data and processes can help target support to vulnerable members not just during crises but also at normal time to enhance the coping capacity of members from marginalized groups (Sapkota et al. 2019; Gentle et al. 2020).

9.4.2 Community Forestry and Social Resilience

By bringing together local community members to pursue collective actions in protecting and managing the forest resources they depend upon, CF contributes to enhancing social capital. The provisions in CF programs to promote equity and inclusion in managing and benefitting from the forest resources and community development contributes to strengthening social capital (Roslinda et al. 2017). Fair representation of ethnic minorities such as Mon and Karen in the Heinze community in Myanmar and enabling environment for their effective roles contributed to social capital, thereby enhancing social resilience (Sapkota et al. 2019). This was observed in all four cases; their leadership body represented minorities and marginalized community members, including poor members, and contributed to fulfilling their forest product and livelihood needs. With women in leadership, they attempt to identify and address issues that women face in managing forest resources as well as community development (Giri and Darnhofer 2010).

The leadership of women in addressing issues faced by women was conspicuous in Bishnupur while less so in other communities, possibly because of varying level of gender inclusion in community forestry programs across the countries, although all communities made conscious efforts for gender and social inclusion as required by CF programs. Unlike CF programs in other study countries, CF programs in Nepal have made it mandatory to have at least half of the leadership positions filled by women, equitably share benefits between men and women, and have also promoted all women CFUGs (DoF 2009). Given that women are disproportionately exposed to crises, due to existing gender inequalities in study countries and beyond, these conscious efforts of gender inclusion at programmatic and user groups level are required to address the issues that contribute to the vulnerability of women, which in turn affect families and communities (Agarwal 2018).

Similarly, collective actions from community members, such as during forest patrol in Samaky Trapeang Totim, Heinze, and Muong Phu and community development in Bishnupur, facilitate cooperation among community members and with other actors such as local governments and civil society organizations, enabling co-generation of knowledge in tackling social, economic, or environmental issues faced by community members (Mandrysz 2020). Such acts help protect their resources and help build trust among the members and increase the likelihood of cooperation in dealing crises, as observed by Lin et al. (2019) in other communities in Myanmar. In doing so, CF has been a means to safeguard and apply traditional knowledge in the management and utilization of forest resources as reported in Samaky Trapeang Totim in Cambodia.

9.4.3 Community Forestry and Economic Resilience

The CF provides a stable source of income for local communities at the collective and individual levels. In doing so, all the cases demonstrated that CF provides an array of non-timber forest products such as honey (Muong Phu and Bishnupur), Chrysanthemum tea, also known as yellow flower tea (Muong Phu), bamboo shoots, mushroom and different herbs (Samaky Trapeang Totim), dog fruit (Heinze) for the livelihood of the community members who consume them or sell in markets to make small incomes. Additionally, the CFUGs promoted home gardening, such as in Heinze and Bishnupur, by providing seedlings. CF contributed to the livelihood of the community members, particularly those dependent on agriculture, by protecting water sources, controlling soil erosion, protecting biodiversity, which potentially help, for example, in pollination, and control pests in their farms.

Microcredit programs such as CF credit in Cambodia and revolving fund in Myanmar were also found critical in helping vulnerable households to survive at the time of crisis or increase their income during normal times. For example, in Heinze, grass mowers purchased using money from revolving funds served as a source of income for low-income households, providing them financial access. It is important given that many of the poor community members cannot access such resources due to a combination of multiple reasons, such as lack of documentation and service costs and inability to follow often tedious procedures of financial institutions to secure loans (Vichet 2019). That was evident in Samaky Trapeang Totim where community members, who lost sources of income, accessed credit to survive during COVID-19 restrictions. Families with access to such financial access can better tackle risk by investing to improve their condition and enhance resilience (Lin et al. 2019). RECOFTC (2021), from a larger set of CFUGs from seven Asian countries, including those covered in this research, also highlighted the importance of such credit schemes to help CFUG members hardly hit by the pandemic.

While CF provided finance and materials for development at the community level, for example, Heinze community provided 6 tons of timber for the construction of a local monastery, indicating positive roles of CF in the conservation of local culture. Such structures are handy at the time of crisis. Gentle et al. (2020) reported that more than 1400 community forest user groups in Nepal offered their buildings as quarantine centers, in addition to spending USD 99,000 to donate food and non-food items to people in need and donated more than USD 70,000 to local government relief funds, benefitting more than 150,000 people in total during the COVID-19 crisis in 2020.

CF can be a source of income by providing environmental services, as demonstrated in the Muong Phu community in Viet Nam. If supported by policies and programs, CF brings stable supply of financial resources to the community, which can be used for forest protection, community development, and to cover household expenses, as reported by members of the Muong Phu community in Viet Nam. A notable observation was that while other sources of income were affected at the time of the COVID-19 pandemic, the Muong Phu community continued to receive the money from PFES, suggesting the stability that CF can contribute if supported with similar payment mechanisms for the services provided by communities. This benefit of continued transactions even during COVID-19 restrictions also contributed to increasing the attractiveness of trade of environmental services. In addition, other outcomes of payment of environmental service schemes such as equity, participation, livelihoods, and environmental sustainability also contribute to enhancing the resilience of SES (Adhikari and Agrawal 2013).

9.4.4 Community Forestry and Ecological Resilience

All the four cases demonstrate the increased protection and restoration of their forests with support from local communities, a finding reported very widely such as by Luintel et al. 2018 and Niraula et al. 2013. Our cases also confirm such findings and report reduced illegal logging, for example, by up to 95% in Heinze, within 3 years between 2017 and 2021. The communities reported that after the forest was handed over to the local communities, their protection efforts, such as through forest patrol, contributed to such a high reduction in illegal logging as well as forest fire incidences. They contributed in the maintenance of water resources in the forest as well as biodiversity conservation, which was indicated by 35% more stock of valuable trees of *Xylia* and *Dipterocarpus* in Heinze community forest.

Similarly, the communities prioritize nature-based solutions such as plantations, forest restoration, as evidenced by Bishnupur and Heinze CFUGs, to tackle climate hazards. The plantation of indigenous and multi-purpose grass/bamboo and fruit species as done in Bishnupur, which were planted to provide protection from flood and soil erosion, contributes to improving ecological conditions, including by making forest resilient against disease outbreaks and harsh climatic conditions (Samadharmam et al. 2021).

9.4.5 Areas for Improvements

While the presented cases and literature suggest substantial contribution of CF programs in enhancing the resilience of SES through multiple positive changes as mentioned above, they also highlight areas for improvement for the CF programs to optimally contribute in enhancing the resilience of SESs. One of such areas is reducing inequality. As evident in two cases, except in Samaky Trapeang Totim and Bishnupur, men dominated in the CFMCs. While the fair representation of marginalized groups in the leadership alone is not sufficient to mainstream such groups in decision-making process, because of persistent discriminatory social norms, and unequal representation, posing a risk of reinforcing inequalities and reducing the adaptive capacity of marginalized groups (Sapkota et al. 2019). In addition, the CF stakeholders, particularly the governments, can better recognize gender inequality in the interactions in the SES and address them through a combination of inclusive policies, awareness, and leadership capacity development (Bhattarai 2020).

Similarly, CFUG capacities were found limited to support their members at the time of crisis, negatively affecting economic resilience. Their capacities are apparently constrained by a combination of limited income resulting from lack of merchantable non-timber forest products and regulatory barriers to harvest and sell timber; reliance only on CFUG fund for microcredit schemes and limited collaboration with local governments (Gritten et al. 2015; Sapkota et al. 2020). A study conducted by RECOFTC (2021) in seven Asian countries about COVID-19-related impacts revealed that if supported with stronger policies and capacities, and handed over adequate and productive forest areas and rights to sustainable harvest and selling of forest products, CFUGs can increase their members with improved access to finance, financial literacy, and service by partnering with microfinance, local government, and private-sector actors.

One of the key areas that governments and CF stakeholders can pay more attention to is amplifying contributions of CF programs in resilience building by integrating climate adaptation, and disaster risk reduction in community forestry programs, going beyond having forest protection, and improving biophysical characteristics of forests as the objectives of community forestry programs. Effective monitoring of CF programs is still an issue, which poses a challenge in improving CF programs and their contribution to enhancing social economic resilience, a point also highlighted by Lin et al. (2019). Efforts to address the issues are likely complemented by strengthening review systems of CF programs as well as stronger linkage of other development processes, which includes integration of CF programs in the larger system of multi-level and nested governance (Ojha et al. 2016). This includes close collaboration with local government agencies in adaptation planning and disaster preparedness in a systematic manner (Cretney 2016; Gentle et al. 2020). Such actions have the potential to enhance interactions among the CF members and with their resources and with external actors to strengthen institutional resilience, thereby enabling CFs to make optimal contributions to enhancing the resilience of social-ecological systems.

9.5 Conclusions

This article demonstrated that community forestry can have a strong contribution in enhancing the resilience of entire social-ecological systems, going well beyond biophysical improvements of forests that literature has highlighted. In doing so, community forestry helps enhance and systematize interactions among community members, with external actors, and with forest resources (Ostrom 2009). The CF also contributes substantially to enhancing institutional, social, economic, and ecological resilience, as reported in four case studies.

The contributions of CF across those indicators of resilience vary across the SES contexts, such as attributes of users, resources, interactions, regulatory regimes, and market conditions. This also means that the performance of CF-based SES can be improved by improving such factors. While four cases are highly inadequate to suggest recommendations, the article complements the body of literature such as Sapkota et al. (2020) and those compiled by Gilmour (2016) in highlighting the importance of strengthening CF programs to enhance the resilience of the SES where local community manage forests. Key elements that are highlighted are development of CF leadership, having strong gender inclusive provisions, securing forest tenure of forest communities, providing capacity support, and linking forest managing communities to the market of forest products and services. CF programs and their contributions are strengthened by integrating them particularly with climate adaptation and disaster risk reduction programs of governments and more strongly embedding CF programs in local development planning.

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Biodiversity and Biomass Carbon Dynamics: Insights from Long-Term Monitoring in the Western Ghats

10

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Abstract

Management and conservation of forests are subject to pressures and disturbances. Planning and management of forests for conservation require information on the biodiversity, socio-economic dependence, forest biomass, and carbon. Long-term studies help generate such information on the structure and function of forests. The current study was conducted in the Uttara Kannada District of Karnataka in the Western Ghats region. The dynamics of forest ecosystems was studied through permanent plots of 1 ha in the evergreen and deciduous forest types, and the socio-economic aspects through household surveys in villages in the proximity of the permanent plots, for assessing the dependence on forests. The biomass estimates for the evergreen forest plots were 301–341 t/ha and those for deciduous forest plots were 258–336 t/ha. This is despite large dependence of households in the range of 10–48% on the forests for food, fodder, firewood, manure, and other NTFPs. Long-term data on the growth

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and mortality rates of economically important species, forest carbon balance, and the impact of climate change on forest composition are central to effective management. However, this information is rarely integrated within the policymaking process. This data could be utilized through integration at three points—the policy window, the decision window, and the networking window. Creating these policy, decision and networking windows will allow use of information from permanent plots for effective and efficient management of forest ecosystems, making them resilient to systemic and chronic shocks—both climate and non-climate.

Keywords

Permanent plots · Biomass · NTFPs · Disturbance · Forest management

10.1 Introduction

Forests support the sustenance of human population, while at the same time, they are under the influence of climate change and human-induced pressures, affecting sustainability (Kumar et al. 2018; Savita Kumar et al. 2018). Forests provide vital habitat for biodiversity (Brockerhoff et al. 2017). Further, biodiverse forests are resilient and provide a multitude of ecosystem services—trees absorb and store large quantities of carbon and provide food, fodder, fibre, etc. (UNFAO 2015). Forest ecosystems are a sink as well as a source of carbon and play an important role in the global carbon cycle. Globally, 50% of the total carbon in tropical forests is stored in aboveground biomass and 50% is stored in the top 1 m of the soil (Dixon et al. 1994).

The functioning of a forest ecosystem can be gauged by monitoring important parameters like its biomass and production. The resilience of tropical forests to management interventions—intended or unintended—is essential to ensure long-term functioning and provisioning of ecosystem services. It is generally believed that disturbance will increase the vulnerability of an ecosystem to other environmental change agents (Turner et al. 2016). There are also a few theories that recognize the ability of disturbance to enhance resilience or reduce vulnerability as well (Anke and White 2019). Recovery of aboveground biomass will determine largely the carbon sequestration potential of forests. The potential for climate change mitigation is also related to restoration of forest attributes such as timber stocks (Feldpausch et al. 2006), biodiversity, and species composition (Chazdon et al. 2007).

Management and conservation of forests are subject to pressures and disturbances, and this may also vary according to composition of forests, proximity to human population, and traditional forest use in a region. Therefore, any planning and management of forests for conservation require information on the biodiversity, socio-economic dependence, forest biomass, and carbon. Long-term studies or permanent plots help understand the structure and function of forests serving as important forest management tools.

The current study was conducted as part of a global project of Earthwatch Institute under the HSBC Climate Partnership programme during 2009–2012. Subsequently, Indian Institute of Science, Bengaluru, continued monitoring of plots up till 2020.

10.2 Study Area and Methods

The Western Ghats extends over five states of southern India, including Karnataka. About 60% of the Western Ghats is in Karnataka, spanning 11 districts. About 50 million people inhabit the Western Ghats, which spreads over an area of 1,64,280 km^2 (MoEFCC and GiZ 2014). Uttara Kannada district that lies between 13° 55′ to 15° 31’ N lat 74° 9′ to 75° 10′ E long and receives an average annual rainfall of 3500 mm near the coast to more than 5000 mm along the ridge of the hills, mainly from the southwest monsoon (Fig. 10.1), is one of the districts. The Western Ghats, which run parallel to the west coast, passes through Uttara Kannada district, dividing it into two distinct zones namely, the upland country along the Ghats, at an elevation of 675 m above sea level, and a narrow coastal strip. The total geographic area of the district is 1,027,700 ha and forests account for 79% of the total area (ISFR 2021). Of this, 116,788 ha is very dense forest with a tree canopy cover of

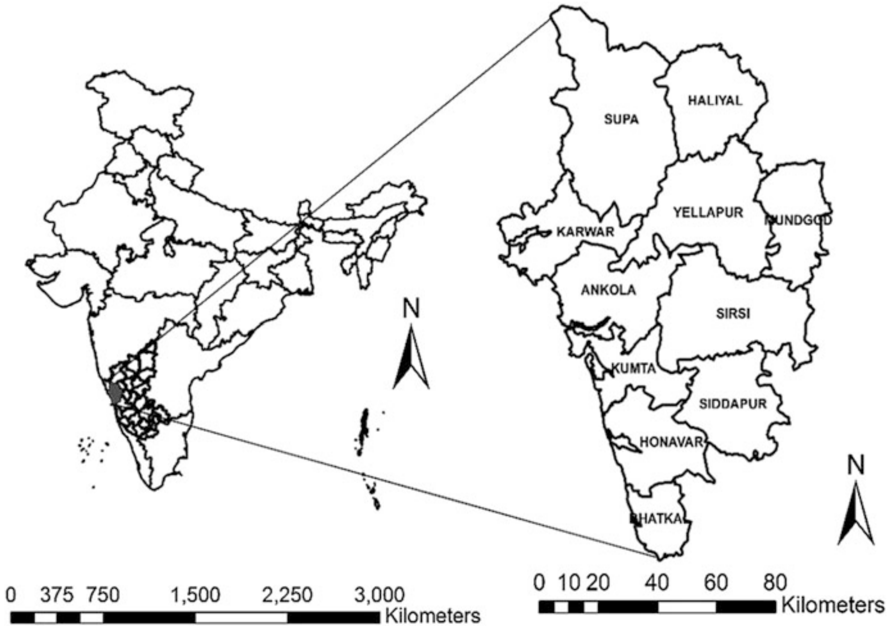

Fig. 10.1 Study area

70% and above, 585,660 ha is moderately dense forest with a canopy cover of 40–70%, and 110,646 ha is open forest with a canopy cover of 10–40%.

The qualitative aspects of the forests of Western Ghats have been described by Champion and Seth (1968), and Pascal and Pelissier (1996). Further, Bhat et al. (2000a, b), Pomeroy and Primack (2003), and Murthy et al. (2016) present a quantitative assessment and dynamics of this region. The vegetation of the district is evergreen or semi-evergreen along the slopes, and to the east of the ridge, it is predominantly moist deciduous (Pascal 1986).

10.2.1 Ecological Monitoring

The dynamics of forest ecosystems in the Western Ghats forests of Uttara Kannada district has been studied through permanent plots of 1 ha (100 × 100 m)—6 plots laid in the evergreen and deciduous forest types of Uttara Kannada district (Fig. 10.2). At all sites, woody plants, >10 cm in GBH (girth at breast height), have been mapped and identified to the species level following Cooke (1967). In case of uncertainty, species were identified up to genera or family level and doubtful

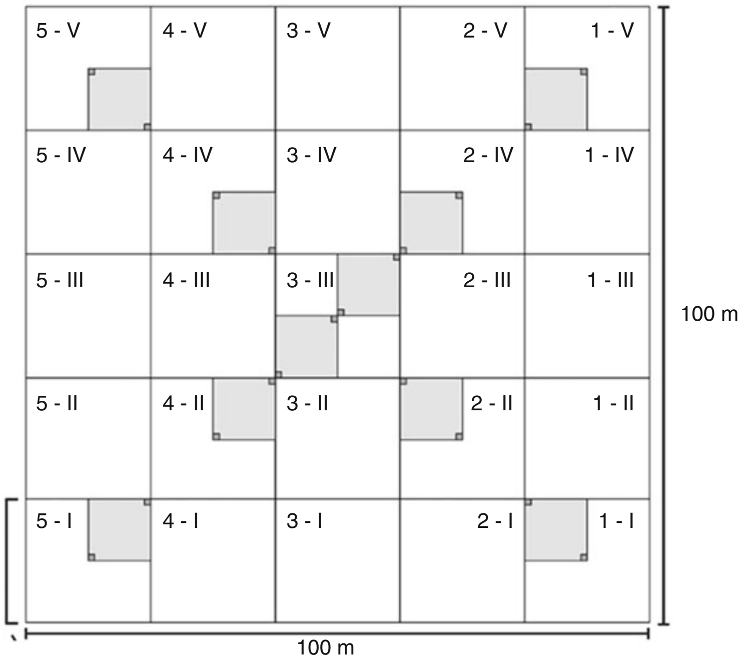

Fig. 10.2 Plot layout for assessment of biomass and carbon in evergreen and deciduous forest types of Uttara Kannada district (the shaded blocks are shrub plots)

entities recorded as Unknown I, II, III. . . etc., with due care to ensure that within a plot Unknown I is a unique species. Trees with branches of GBH >10 cm were noted as stems and recorded with a unique identification number along with the suffix A, B, C etc. DBH of all the stems was recorded. At the point of measurement of DBH, which is 1.3 m from the ground, a red strip was painted and trees assigned a unique number and tagged using embossed metal tags.

Total aboveground biomass was estimated by applying the allometric equation developed by Murali et al. (2005). First enumeration of the plots was done in 2009 (baseline). Re-enumeration of the plots was conducted during 2011, 2014, and 2020. Basal area was calculated for the six 1-ha forest plots, and aboveground living biomass computed following Murali et al. (2005). The carbon stock at each forest site was estimated assuming it accounts for 45%[1] of the aboveground biomass. Belowground biomass was estimated using the IPCC default factor of 0.24. Changes in biomass and carbon stock in the forest plots have been computed by deducting the stock values recorded during the baseline year from stocks of biomass and carbon during re-enumeration years. This includes stocks contributed by recruits during the re-enumeration years.

Monitoring of biomass and carbon through permanent plots helps understand the forest dynamics, a requirement to arrive at rates of carbon fixation by a forest type in a region (Bhat et al. 2003). In this chapter, tree species composition, biomass, and carbon stock dynamics over the 10-year period of 2009–2020 in six 1-ha permanent plots—3 each from evergreen (Ekkambi, Hosur, and Tattikai) and deciduous (Hudelakoppa, Malgi, and Togralli) forest types, located close to settlements, are presented.

10.2.2 Assessment of Community Dependence

Forests provide a range of products and services to local communities. An assessment of the dependence of communities on forests has been carried out in the villages spanning 457 households, close to the ecological plots in evergreen and deciduous forests during 2014. These villages are located within 2–3 km from the forest plots. A questionnaire survey was conducted to collect information from households on the diversity of non-timber forest products (NTFPs) extracted. The selected villages and the number of households sampled in each of these villages are presented in Table 10.1. Attempt was made to cover all the households for 100% sampling; however, not all of the households could be surveyed due to unavailability of some of the members.

[1] https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp3/Anx_3A_1_Data_Tables.pdf

Table 10.1 Total number of households and number of households sampled

Forest type/ region	Village	Total number of households	Number of sampled households
Evergreen	Ekkambi	110	101
	Hosur	24	22
	Tattikai	21	20
Deciduous	Hudelakoppa	41	39
	Malgi	98	90
	Togralli	55	50

10.3 Trends in Number of Species and Species Richness

Species richness is the number of different species represented in an ecological community, landscape, or region. Table 10.2 presents the number of species and the number of individuals representing each of the species in the study locations according to forest type.

Evergreen Plots: The number of tree species varied between 52 in Ekkambi and 79 in Tattikai during the baseline enumeration in 2009. During 2020, the number of species in the evergreen plots ranged from 50 in Ekkambi to 79 in Tattikai. While there is a reduction in the number of species over the 10-year monitoring period in Ekkambi, in Hosur, the number of species has increased by 4, and in Tattikai, it is the same. It is interesting to note that among the three evergreen plots, the number of species has remained more or less constant in Tattikai during the different enumeration years. However, in Ekkambi, the number of species increased from 52 to 54 in 2011 but then declined to 50 in 2020. In the evergreen plots, the number of individuals varied between 1457 and 2184 during the baseline enumeration. It was highest in Tattikai, followed by Ekkambi, and least in Hosur. The same trend in number of species continued in 2020, but the number of individuals has decreased in Ekkambi and Hosur and increased marginally in Tattikai.

Table 10.2 Number of species and individuals in evergreen and deciduous plots during different enumeration years

	2009		2011		2014		2020	
Location	No. of species	No. of stems	No. of species	No. of stems	No. of species	No. of stems	No. of species	No. of stems
Evergreen								
Ekkambi	52	1692	54	1656	54	1610	50	1623
Hosur	56	1457	62	1409	61	1389	60	1396
Tattikai	79	2184	78	2131	79	2196	79	2187
Deciduous								
Hudelakoppa	61	1573	56	1489	55	1622	60	1639
Malgi	29	451	31	468	32	483	30	498
Togralli	73	1388	75	1515	75	1358	76	1476

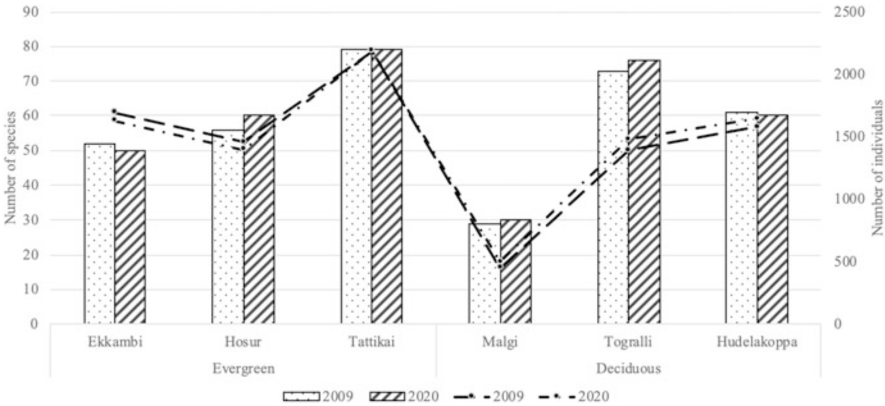

Fig. 10.3 Number of species and the number of individuals in the evergreen and deciduous plots during 2009 and 2020

Deciduous Plots: The number of species was least in Malgi and highest in Togralli among the deciduous plots during baseline enumeration in 2009. In 2020, the number of species has decreased marginally in Hudelakoppa but increased by 3 species in Togralli and one species in Malgi. The trends in change in the number of species are consistent during the different enumeration years. The number of individuals belonging to the different species in the three deciduous plots ranged from 451 in Malgi to 1573 in Hudelakoppa during the baseline enumeration. This has increased to 498 and 1639 in Malgi and Hudelakoppa, respectively, and in Togralli also, an increase in the number of individuals is recorded over the 10-year monitoring period.

Figure 10.3 presents the average number of species and the number of individuals in evergreen and deciduous plots during the baseline enumeration in 2009 and the last enumeration during 2020.

The average number of species in the evergreen plots however remained more or less constant (62 and 63 species during 2009 and 2020, respectively) over the 10-year period, but with a decline in the number of individuals (Fig. 10.3). The average number of species in the deciduous plots has also remained almost constant (54 and 55 species during 2009 and 2020, respectively) during this period, but the number of individuals representing these species has increased (Fig. 10.3).

10.4 Trends in Basal Area

Basal area is an indicator of growing stock and biomass production. Differences in basal area are usually correlated to the density of individuals and the size of stems. It also reflects the age, disturbance, succession stage, and overall productivity of a system.

Evergreen Plots: Basal area of trees in the evergreen plots ranged from 34.68 m^2/ha in Tattikai to 43.53 m^2/ha in Hosur during the baseline enumeration in 2009. In all the three evergreen plots, the basal area of trees has increased during the 10-year period of 2009–2020 (Fig. 10.4). The increase is by about 12% and 13% in Ekkambi and Tattikai, respectively. However, in Hosur, the increase is marginal.

Deciduous Plots: In the deciduous plots, the basal area recorded during the baseline year (2009) ranged from 30.45 m^2/ha in Hudelakoppa to 36.28 m^2/ha in Togralli. In the same plots, the basal area ranged from 31.78 m^2/ha in Hudelakoppa to 41.11 m^2/ha in Togralli during 2020 (Fig. 10.4). The increase in basal area in these plots ranged from 4 to 13% over the 10-year period 2009–2020.

The average basal area recorded in the evergreen plots during 2009 was 38 m^2/ha, and this increased to 41 m^2/ha during 2020 enumeration. Similarly, in the deciduous plots, basal area of 34 m^2/ha was recorded during 2009, and this increased to 37 m^2/ha in 2020.

It can be seen from Fig. 10.4 that among the evergreen as well as deciduous plots, there is a slight decrement in basal area during certain enumeration years, in a few plots. However, over the 10-year period, the basal area has increased across all the plots, in both the forest types.

10.5 Trends in Biomass

Estimated values of aboveground biomass in the different forest plots during the baseline year, i.e. 2009, and after 10 years are given in Table 10.3.

Evergreen Plots: The estimated aboveground biomass stock varied from 277 to 334 t/ha among the evergreen plots during 2009. The lowest biomass stock was in Tattikai and the highest biomass was in Hosur. After 10 years, i.e. during 2020, the biomass stock in Tattikai was still the lowest (301 t/ha), and the highest biomass was estimated for Hosur (341 t/ha). The biomass stock in Ekkambi plot was 284 t/ha in 2009 and 312 t/ha during 2020.

In general, the average aboveground biomass in evergreen plots was 299 t/ha during 2009 and this has increased to 318 t/ha during 2020. If belowground biomass is accounted, the biomass stocks in the evergreen plots would be 376 t/ha during the baseline year, i.e. 2009, and 401 t/ha 10 years later, i.e. in 2020.

Deciduous Plots: Among the deciduous plots, the stocks of biomass were highest in Togralli (287 t/ha) and lowest in Hudelakoppa (249 t/ha) during the baseline enumeration in 2009. However, during 2020, highest biomass stocks were estimated for Malgi (336 t/ha), followed by Togralli (319 t/ha) and Hudelakoppa (258 t/ha).

The average biomass stock in the deciduous plots during 2009 was 274 t/ha during the baseline enumeration in 2009, and this has increased to 304 t/ha during 2020. Add to this the belowground biomass, the stocks would be 345 t/ha and 353 t/ha during 2009 and 2020, respectively.

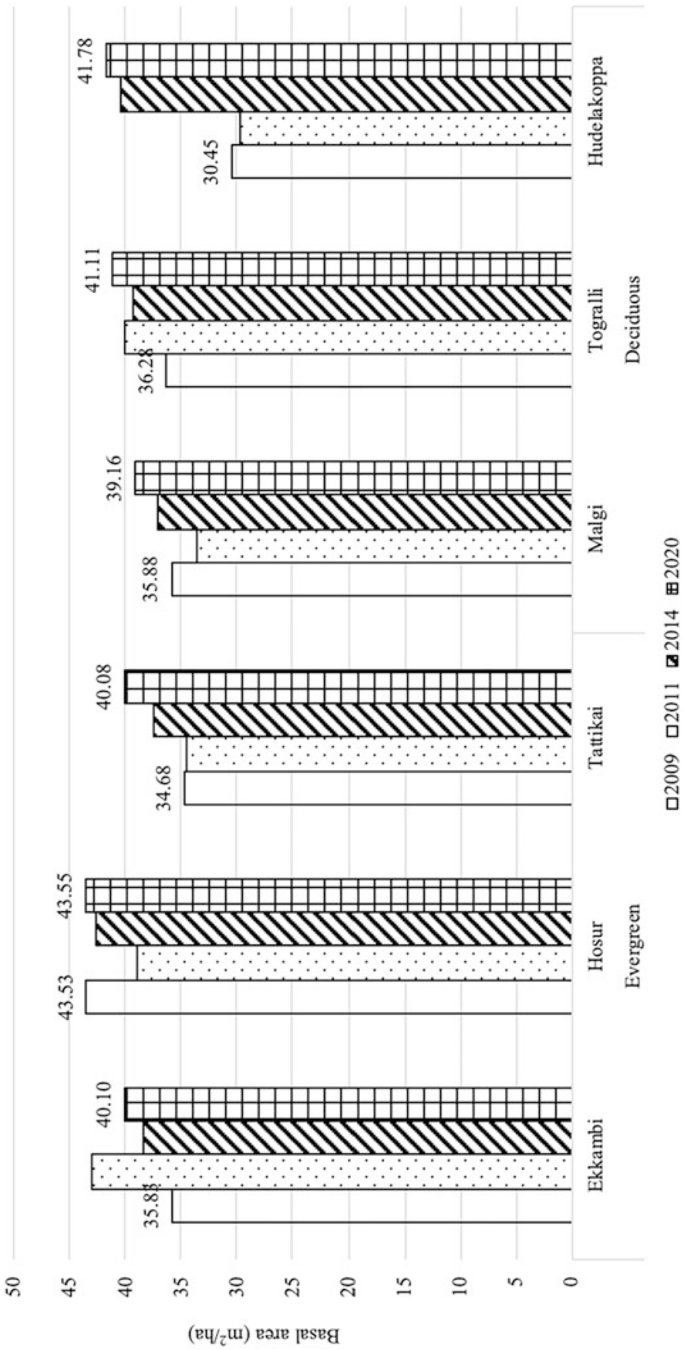

Fig. 10.4 Basal area in evergreen and deciduous plots during different enumeration years

Table 10.3 Trends in aboveground biomass in evergreen and deciduous plots during different enumeration years

	Location	2009	2011	2014	2020
Evergreen	Ekkambi	284	417	342	312
	Hosur	334	385	374	341
	Tattikai	277	348	334	301
	Average + belowground biomass	376	398	390	381
Deciduous	Malgi	285	340	332	336
	Togralli	287	393	348	319
	Hudelakoppa	249	308	356	258
	Average + belowground biomass	345	364	363	353

10.6 Trends in Living Biomass Carbon

Carbon stocks reported here include both aboveground and belowground biomass. Belowground biomass is computed as a fraction of the aboveground biomass. The carbon stocks estimated for the evergreen and deciduous plots are presented in Fig. 10.5.

Evergreen Plots: The carbon stock during the baseline year enumeration was highest for Hosur (190 t/ha) and lowest for Tattikai (157 t/ha). In general, the average carbon stock for evergreen plots was 169 t/ha during 2009. Even after 10 years, i.e. during 2020, the stock in Hosur was the highest (193 t/ha), followed by Ekkambi (177 t/ha), and Tattikai (171 t/ha).

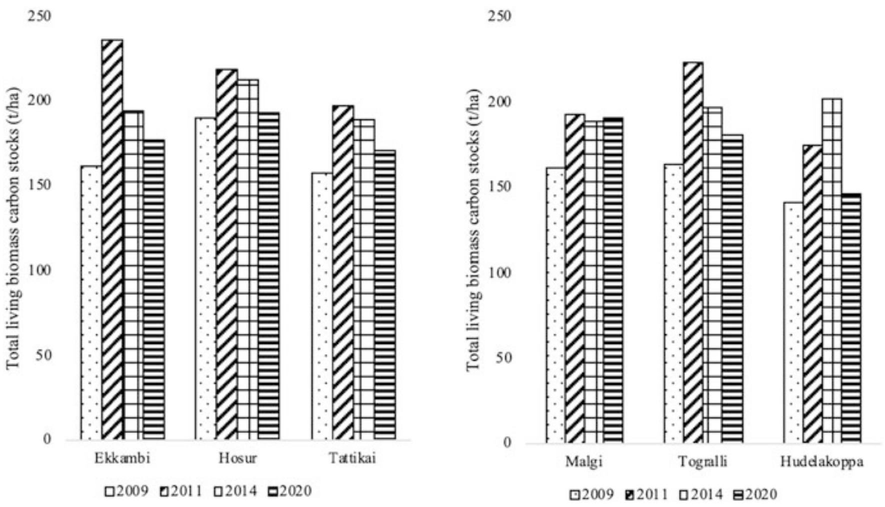

Fig. 10.5 Carbon stocks in living biomass (aboveground+belowground) in evergreen (left) and deciduous (right) plots during different enumeration years

Deciduous Plots: The carbon stock in Togralli was highest (163 t/ha) during the baseline enumeration in 2009. The carbon stock in Malgi was comparable at 161 t/ha, and the lowest was recorded in Hudelakoppa (141 t/ha). Ten year later, in 2020, highest carbon stocks were recorded in Malgi (191 t/ha), followed by Togralli (181 t/ha), and Hudelakoppa (146 t/ha). The average carbon stock in the deciduous plots was 155 t/ha during the baseline enumeration, and during 2020, it was 172 t/ha.

In both the evergreen and deciduous plots, carbon stocks have increased over the 20-year period. The increase is 2–10% in the evergreen plots and 3–18% in the deciduous plots. The average increase in carbon stocks is higher in the deciduous plots (11%), compared with the evergreen plots that have recorded a 7% increase over 10 years.

10.7 Socio-economic Dependence of Communities on Forests in the Western Ghats

Biodiversity and ecosystem processes and services benefit humans directly or indirectly (Daily 1997). Some confer direct benefits such as provision of goods and raw materials such as timber, firewood, fruits, fibre, and medicines and there are other indirect benefits including regulation of hydrology and water flow, carbon stocks, pollination, etc..[2] Household survey in villages in the proximity of the ecological monitoring permanent plots through a questionnaire survey has generated an evidence base for understanding the significance of provisional services provided by the evergreen and deciduous forest types.

The percentage dependence of households on the forests is presented for evergreen and deciduous forest type in Table 10.4. On an average, about 30% of households in a village depend on forests for NTFPs.

The number of NTFP species that provide food, fodder, medicinal, and firewood in evergreen and deciduous forest types is presented in Table 10.5.

Food: Traditionally, local communities collect and consume plant parts such as fruits, seeds, flowers, and leaves. According to Verma et al. (2014), 80% of people in

Table 10.4 Percentage of households collecting tree-based NTFPs from different species

	Location	Percentage of gathering households	Average percentage of gathering households
Evergreen	Ekkambi	13.40%	29.10%
	Hosur	47.60%	
	Tattikai	26.30%	
Deciduous	Malgi	9.60%	28.70%
	Hudelakoppa	34.20%	
	Togralli	42.30%	

[2] https://www.cbd.int/financial/values/unitedkingdom-valueliterature.pdf

Table 10.5 Number of species used as food, fodder, medicine, and for other uses

	Evergreen			Deciduous		
	Ekkambi	Hosur	Tattikai	Malgi	Hudelakoppa	Togralli
Food	14	16	34	7	17	22
Fodder	5	4	3	4	2	3
Fibre	0	0	1	1	1	0
Medicinal	38	48	77	25	45	57
Others[a]	7	7	25	9	16	22

[a]Firewood—Fallen branches and twigs from all tree species in the forests are used as firewood

developing countries use forest products for food and personal care. In the study villages, local communities use many tree species as food or food substitute. Around 40 and 15 tree species are used as food in the evergreen and deciduous forest types, respectively. Some of the dominant species that are collected and used as food and food substitute, and flavouring agents are as follows: kokum butter tree (Garcinia indica), Malabar tamarind (Garcinia cambogia), jack fruit (Artocarpus integrifolia), monkey jack (Artocarpus lakoocha), Malabar plum (Syzygium cuminii), curry leaf tree (Murraya koenigii), Bengal currant (Carissa carandas), wild jujube (Ziziphus rugosa), and mountain sweet thorn (Flacourtia montana).

Fodder and Manure: Tree leaves are gathered from the forests for two purposes: (1) as feed for livestock and (2) to spread on the cattle shed floor. In the villages in the proximity of evergreen forest plots, six tree species are collected and used as fodder, and in the villages close to deciduous forest plots, five species are used as fodder. These include the following: beechwood (Gmelina arborea), Daminiya/Indian linden (Grewia tiliifolia), Ceylon oak (Schleichera trijuga), dog teak (Dillenia pentagyna), and crepe myrtle (Lagerstroemia parviflora). In addition to these, the lops and tops of other species are also collected by local communities for use as fodder.

Green manure-yielding species in the plots under study that are collected and used by the local communities include the following: slow match tree (Careya arborea), Bedda nut tree (Terminalia bellirica), myrobalan (Terminalia chebula), Vetti (Aporosa lindleyana), Macarange (Macaranga peltata), Ukshi (Calycopteris floribunda), and common Indian linden (Grewia tiliifolia).

Medicinal Purposes: The number of species used for medicinal purposes ranged from 38 to 71 in the evergreen forest type and 25–57 in the deciduous forest type. Some of the commonly collected medicinal plants in the study villages include the following: Pisa (Actinodaphne hookeri), Ash Sheora (Glycosmis pentaphylla), Ukshi (Calycopteris floribunda), cinnamon (Cinnamomum zeylanicum), Indian gooseberry (Emblica officinalis), Raktamara (Knema attenuata), Mappia (Nothapodytes nimmoniana), wild nutmeg (Myristica beddomei), Bedda nut tree (Terminalia bellirica), and Myrobalan (Terminalia chebula).

Fibre and Other Uses: A number of species provide fibre and some such species found in the evergreen and deciduous plots include the following: common Kapok tree (Ceiba pentandra), Indian linden (Grewia tiliifolia), and black varnish tree (Holigarna arnottiana). These species in the study plots are also used for other purposes including as an essential oil, for extraction of dyes, as larvicide and insecticide, as a fish poison and in sericulture. While the extract of English Clove (Syzygium aromaticum) is used for termite resistance, the fruit extract of Beechwood (Gmelina arborea) is used as a polishing fluid, and Sapindus spp. is used commercially for the preparation of soaps and other cosmetic products.

Firewood: Firewood is the main source of energy to the rural population for cooking and heating purposes (Komala and Devi Prasad 2016). Wood is an important product in the Western Ghats—used for processing of areca palm nuts, cardamom, cashew, and other agricultural produce. The quantity of firewood available for extraction ranged from 134 to 164 tonnes/ha in the evergreen forest plots, and it was 85–116 tonnes/ha in the deciduous forest plots.

There is thus a large dependence of communities on the forests for multiple NTFPs, and according to Murthy et al. (2014), it contributes to INR 1199 and INR 3561/household in the evergreen and deciduous zones, respectively.

10.8 Long-Term Dynamics of Forest Ecosystems in the Context of Socio-economic Dependence of Communities

The biomass and carbon stocks estimated in the evergreen and deciduous forests of Uttara Kannada show that tropical secondary forests are storehouses of carbon. The biomass estimates of the evergreen (301–341 t/ha) and deciduous (258–336 t/ha) forests during 2020 are comparable to the standing biomass values reported for other primary neotropical forests (Gerwing and Farias 2000; Chave et al. 2001; Keller and Hurtt 2001). It is also comparable to mean aboveground biomass reported for the Amazonian forests (289 t/ha) by Malhi et al. (2006) and African tropical forests (395.7 t/ha) as reported by Lewis et al. (2013). The mean aboveground carbon stock estimated for the deciduous plots was 137 tC/ha which is slightly higher than the range reported globally (14–123 tC/ha) by Murphy and Lugo (1986), and Gandhi and Sundarapandian (2017) for tropical deciduous forests.

Interestingly, the evergreen and deciduous forest plots in Uttara Kannada, although in the proximity of settlements, and with significant dependence of communities, have high biodiversity, as well as stocks of biomass and carbon, that are comparable with other tropical forests in the region. This is an important finding in the context of the district, which has about 10–48% of households dependent on the forests for food, fodder, firewood, manure, and other NTFPs. Murthy et al. (2014) also report a large dependence of local communities on the forests in the districts—50% of the households are dependent on forests for a range of forest products. This is evidence of the fact that communities are not over extracting forest produce. This is opposed to reports of tropical forests being subject to over extraction, and different forms of biotic interferences, resulting in them being degraded and deforested, in extreme cases.

In the study sites in Uttara Kannada, forests are assimilating carbon at the rate of 0.4–2.9 t/ha/year, with an average rate of 1.42 t/ha/year. The sites have gained biomass and carbon over a 10-year period. This gain could be because of stem growth or by recruits. Considering these, it is evident that both evergreen and deciduous forests have accumulated biomass and sequestered carbon of 11.07 t/ha and 17.31 t/ha, respectively, with an annual carbon incorporation rate of 1.11 and 1.73 t/ha/year in evergreen and deciduous forests, respectively. 1.31 t/ha/year Phillips et al. (1998) report a carbon accumulation rate of 0.74 ± 0.34 t/ha/year in neotropical forests. Bhat et al. (2003) report a carbon accumulation rate of 1.31 t/ha/year for forests in the same region.

It is interesting to note that the forest plots are accumulating biomass and carbon in spite of the dependence of local people on these forests, for meeting their requirements of firewood, leaf manure, fodder, etc. This could possibly be attributed to the fact that when there is intermediate level of disturbance, the number of species increases (Connell 1978). According to Montagnini and Porras (1998), differences in the carbon fixing rates of mixed species stands lead to relatively higher capacity of such stands to produce higher level of biomass. Further, disturbance in forests is reported to promote other species to invade while also causing existing individuals to grow at a faster rate (Oshima and Takahashi 2020). This is because, on the one hand, disturbance could promote biomass recovery owing to enhanced growth as a result of increased resource availability, reduced site occupancy, and competition. Brown and Lugo (1982) report higher accumulation of biomass and carbon in forests post-disturbance. In the study sites, the forests are natural forests with mixed species and have been subject to some level of disturbance. Such disturbances may have favoured higher incorporation of carbon into the forest plots. Thus, biomass recovery is driven by growth of the surviving trees as well as recruits, following disturbance and this according to Miller et al. (2011) could be affected by disturbance regime or site conditions and remaining biological legacies (Chazdon 2003).

10.9 Long-Term Dynamics of Forest Ecosystems: Implications for Forest Conservation and Management

Ecologists have long recognized that disturbances can drive ecological system dynamics (Grimm Nancy et al. 2017). Disturbance is defined as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment" (Pickett and White 1985). Across ecosystems, the drivers of disturbance are shifting and the resilience of systems to disturbance are changing, and both are projected to shift because of global change (Turner et al. 2016; Ummenhofer and Meehl 2017). It has been observed that "high levels of biodiversity are effective and essential for ecosystems to endure environmental changes and retain their fundamental functionality, largely contributing to the maintenance of resilience in ecosystems" (Elmqvist et al. 2003; Furukawa Sasaki et al. 2015).

Although Indian forest sector has comparatively, a wealth of information due to the number of long-term research studies—conducted by federal and state forestry research organizations and institutions, there remains a need to match these with international protocols set for long-term monitoring sites. Tripathi (2010) highlighted its need and suggested that it is possible by joining the ongoing International Long-Term Ecological Research (ILTER) networks or establishing country's own network in different ecoregions. A number of studies highlight that Long-term Ecological Research (LTER) and monitoring provide key insights in ecology, environmental change, natural resource management, and biodiversity conservation (Lindenmayer et al. 2012; Haase et al. 2018; Mirtl et al. 2018; Negi Vikram et al. 2019).

An ambitious multi-institutional, multi-disciplinary, all India coordinated project "Long-Term Ecological Observatories (LTEO) programme" has been launched by the Ministry of Environment, Forest and Climate Change, Government of India, with the Indian Institute of Science, Bengaluru. This programme will monitor a range of themes and taxa across the Indian subcontinent including soil, forests, grasslands, invertebrates, fish, herpetofauna, birds, animal movement, and marine ecosystems.[3]

Long-term data from permanent forest inventory plots have much to offer for management and conservation of tropical forest landscapes. Knowledge of the growth and mortality rates of economically important species, forest carbon balance, and the impact of climate change on forest composition are all central to effective management. However, this information is rarely integrated within the policymaking process. Outcomes of long-term monitoring programmes will help design conservation actions for increasing forest resilience—with improved understanding of the dynamics of forest ecosystems that are accessed by humans—inadvertently or advertently disturbing the forest, which are being impacted by changes in the climate as well.

Such improved understanding of the problem which emerges from long-term monitoring can influence forest management and also provide opportunities to engage with multiple stakeholders—both managers and users. However, to ensure data from permanent plots are used, there is a need for three windows, namely: (1) identification of opportunities to integrate data within policymaking—could be termed the "policy-window"; (2) development of long-term relationship between scientists and policymakers—could be termed the "decision-window"; and (3) data sharing among different participants and integration of plot networks, particularly between institutions in the global north and those in tropical countries—could be termed the "networking-window." Creating these policy, decision, and networking windows will allow information emerging from permanent plots to make tangible contribution to management of tropical forests that are resilient and can withstand both systemic and chronic shocks—both climate and non-climate.

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[3] https://lteo.iisc.ac.in/

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Peri-urban Protected Forests in Peril: Insights from Case Studies in Two Indian Megacities

11

B. Dhanya, Samudyatha Ramananda, Rupal Jain, and Pragyi Baghel

Abstract

Urbanisation has emerged as a major driver of ecosystem changes with mixed outcomes on the sustainability of production and protected landscapes in peripheries of cities. Urban demand for land, water and other resources significantly impacts peri-urban protected forests, a vital green infrastructure catering to multiple ecosystem services needs of cities. We assessed the ramifications of urban growth on social-ecological interactions around peri-urban protected areas (PAs) located in two megacities of India, using literature review and analysis of media content. Our analysis indicates that urban development creates negative impacts on the selected PAs in terms of land-use changes and the complexity of governance. Provisioning ecosystem service uses from PAs were found declining, while cultural service uses and ecosystem disservices were found prominent in both cases. Analysis of media coverage showed a greater frequency of themes such as infrastructure development projects, mining etc. indicating substantial media attention on the threats to urban PAs. The chapter further discusses the implications of urbanisation for forest conservation and ecosystem-dependent livelihoods in peri-urban spaces and suggests ways to integrate protected forests in the urban fabric.

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Keywords

Urbanisation · Livelihoods · Ecosystem services · Land use · Governance · Human-wildlife conflict

11.1 Introduction

Over 18% of the world's forest area is legally protected as national parks, conservation areas and game reserves (FAO 2020). The global network of PAs has expanded from 14.7% of land and inland waters in 2016 to 15.4% in 2020 (Secretariat of the Convention on Biological Diversity 2020). Urban regions cover only around 3% of the global terrestrial surface area but exert a disproportionate influence both on near and far away landscapes as strong catalysts of nature transformations (Colding and Barthel 2013). In many fast-growing cities, the only remaining green patches now are protected forests that increasingly play a central role in providing ecosystem services crucial to human well-being. The critical importance of urban biodiversity and its associated services are being acknowledged better with growing sprawl and infrastructure boom (Devy et al. 2009).

Urban parks and nature reserves build the resilience of cities against the impacts of climate change and natural hazards, reduce the urban heat island effect, improve water retention capacity and enhance local biodiversity (Van Oijstaeijen et al. 2020). They support recreational, educational and cultural services that improve human health and well-being. Urban parks also help people build an 'identity' attached to their landscape enabling conservation action (Harmon 2004). These 'values from nature' have been amplified greatly with the recent COVID-19 pandemic. Coinciding with the pandemic-induced lockdown phase, increased interest in going out and spending time in 'nature' is documented from several cities (Kleinschroth and Kowarik 2020; Ugolini et al. 2020). While multiple services of urban nature reserves are being better appreciated, there is concomitantly a growing recognition of the rebound effects of urban areas on surrounding green spaces. Urban expansion is predicted to fragment or destroy PAs (McKinney 2002) with localized, but cumulatively significant impact (Mcdonald et al. 2008). Urban proximity to nature reserves results in negative impacts such as noise pollution, reduced water quality, vegetation tramping, encroachment, dumping of wastes, etc. (Trzyna 2014).

In the Global South, some of the densest urban settlements are found just outside PAs (e.g. Nairobi National Park in Kenya, Tijuca National Park in Rio de Janeiro, etc.) and the current and projected population growth and urbanisation trends in these cities are predicted to threaten the ecological integrity of these protected forests (Rodary et al. 2018). India together with China and Nigeria will account for 35% of the projected growth of the world's urban population between 2018 and 2050 (UN 2019). This chapter attempts to trace the transformations in people–nature interactions around two peri-urban PAs: Sanjay Gandhi National Park (SGNP) and Bannerghatta National Park (BNP), located near two Indian megacities, namely, Mumbai and Bengaluru, respectively. Using the ecosystem services framework, we characterize the social-ecological linkages around the PAs and chart the trajectory of urbanisation-driven changes in the flow and use of these services. We also seek to unpack the role of governance and institutions in accentuating or ameliorating the impacts of the changes.

11.2 Methodology

11.2.1 Study Area

SGNP and BNP were chosen for this study, given their proximity to the two of the most populous cities of India, namely, Mumbai and Bengaluru (Location map in Fig. 11.1).

Mumbai, India's financial capital and the capital city of the state of Maharashtra has a population of over 20.6 million (UN 2021). The city has witnessed a population growth of 1.26% annually since 2015, making it the most populous city in India and the fourth most populous in the world. The city lies on the west coast of India within latitudes 18° 53′ N and 19° 17′ N and the longitudes 72° 46′ E and 72° 59′ E. The Mumbai Metropolitan Region (MMR) is spread over 6640 km^2 while the Municipal Corporation of Greater Mumbai (MCGM) administers an area divided into Mumbai City (150 km^2) and Mumbai Suburban (446 km^2) revenue districts. The chief constituents of green cover in the city comprise SGNP, along with the mangrove cover in northwest and east, and the hill ranges in the eastern suburbs.

Bengaluru, India's Information Technology (IT) hub is the capital of the state of Karnataka and is located at 12° 39′ N and 13° 30′ N latitudes and at 77° 10′ E and 77° 57′ E longitudes, spreading over an area of 741 km^2 under the local municipal corporation. Bengaluru has a long history of urban settlement that goes back to the 1600s that has profoundly shaped the city's ecology. Post-independence, the city has seen an industry-oriented development, followed by an IT boom that also accelerated residential area expansion (Patil et al. 2018). The city currently is home to 12.7 million, and its population has grown at a rate of 3.56% annually since 2015, making it the third most populous and the fastest growing city in India (UN 2021). Several parks, gardens, lakes and wooded groves make up the city's green infrastructure. Tropical dry deciduous forests constitute about 8.25% of the 2266 km^2 area in the Bengaluru Rural division.

11.2.2 Methods

We used a detailed literature review to glean information on the two protected forests in focus: BNP and SGNP. Transformations in land use and ecology, ecosystem services and their uses, and institutions and governance were used to characterise the changing social-ecological dynamics following the framework applied by Thapa et al. (2021) to analyse the changes in green infrastructure elements in response to

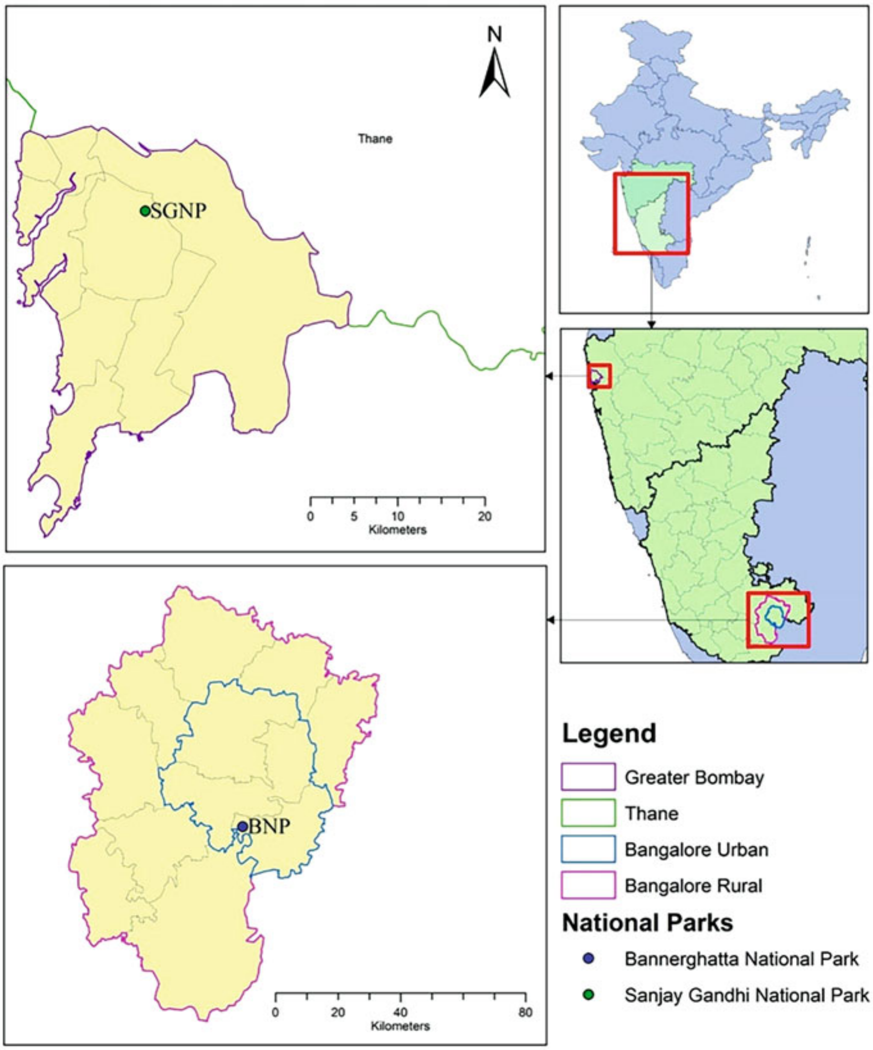


Fig. 11.1 Location maps of BNP and SGNP

urbanisation. We referred to peer-reviewed journal articles from databases including Google Scholar, Science Direct and ResearchGate, government reports and online articles. To fine-tune the review further, we used specific keywords such as 'land use', 'ecosystem services/benefits', 'urbanisation', 'biodiversity', 'human-wildlife conflict', etc. along with the respective PA in focus. Only those literature written in English and published post-2000 were selected for the review.

We also used content analysis to understand the recent trends in media reportage on the two selected protected forests. Weber (1990) defines content analysis as a research method that uses a set of procedures to make valid inferences from the text. Media content analysis began as a systematic method to study mass communication and its propaganda but became popular overtime as a methodology in research. We analysed the content of these PAs in 'Protected Area Updates' published by Kalpavriksh in the past decade (2011–2020). Protected Area Updates are newsletters published every alternate month of the year as a compilation of news reported from PAs across India. The reports are included along with their sources (mostly English dailies) and the date of publication in the PA update. The reports collected were categorised into themes that are relevant to the study and the frequency of the themes were calculated.

11.3 Results

About 38 articles and 10 reports on the two selected PAs were included in the literature review. In the content analysis, the total number of reports on the two PAs reviewed were 65; 12 of BNP and 53 of SGNP. A higher number of media reports on both the PAs were recorded from 2018 and 2019, followed by a dip in 2020, which might be due to the COVID-induced lockdown (Fig. 11.2).

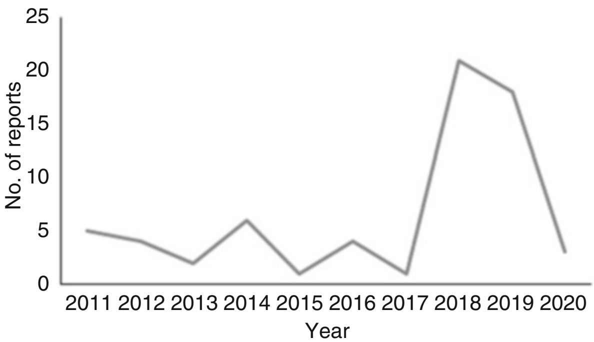
The different dimensions of social-ecological transformations in the two PAs described in the literature and media content are detailed below.

11.3.1 Sanjay Gandhi National Park

11.3.1.1 Social-Ecological Context

SGNP, located in Mumbai, the most populous city of India, is a 'green oasis' in the core of urban sprawl (Jadhav 1995). SGNP geographically falls under Thane District (59.24 km^2) and Mumbai Suburban District (44.44 km^2) (SGNP 2017). SGNP is a major tourist attraction and receives over two and a half million visitors annually (Hadker et al. 1997). Known as 'Krishnagiri National Park' in the pre-independence

Fig. 11.2 No. of reports during 2011–2020 on the selected PAs



era, the park was spread over an area of just 20.26 km^2 but later expanded over to 103 km^2 by acquiring several neighbouring reserve forests.

Located in the Western Ghats of India, SGNP is mountainous, comprising mixed deciduous forests. Lowlands and hill slopes of the parking area are dominated by genera such as *Tectona, Garuga, Madhuca, Adina, Ficus, Albizzia, Terminalia, Grewia, Holarrhena, Firmiana, Dalbergia, Caraya, Butea* and various bamboos (SGNP 2017). On the upper slope of the forest, Asoka *(Saraca asoca)* patches are found predominantly (SGNP 2017). The park is home to more than 40 species of mammals, 1000 species of plants, 251 species of birds and has a huge diversity of fishes (Sen and Pattanaik 2016). Rich in biodiversity and aesthetics, SGNP caters not only to the recreational needs of urban dwellers but also fulfils the substantial water requirements of the city from the Tulsi and Vihar lakes located within the park (Jadhav 1995).

The park has been home to indigenous communities as early as the third century BC. While Warlis make up the majority, there are other tribal communities such as Mahadev Kolis, Malhar Kolis and Thakurs as well, but in smaller numbers (Landy 2014). There are 44 tribal hamlets with 1800 tribal families living in settlements known as 'padas' (Sen and Pattanaik 2016). Warli community is renowned for their distinctive paintings with geometric figures inspired by their observations of nature, though such traditional livelihood means are found insufficient for living now (Varshney 2018). At present most of them have shifted to other occupations such as caretakers of animals in SGNP, or as guards, cleaners etc. with the FD (Forest Department) or even to jobs outside the park as rag pickers, street vendors, sweepers, etc. (Sen and Pattanaik 2015).

11.3.1.2 Land Use and Ecosystem Changes

In a recent study, a positive change of 88% in forest land from 1978 to 2020 was reported for SGNP (with 5 km of buffer) due to the addition of new areas (CPCB 2021). The same study showed a decrease in mangrove areas by 34.4%, water bodies by 38% and agriculture by 81.8% within the same time span. A huge increase of 96% was noticed in settlements during the years 1978–2020 in the park including a buffer of 5 km and such settlements are often politically supported (Shashidharan and Quadros 2013; CPCB 2021). However, within the park boundaries, settlement area grew till the year 2000 and then showed a decline, resulting in an overall decrease of 27.38% from the year 1987 to 2020 (CPCB 2021). Zérah (2007) also estimates a loss of 27 ha of forest in 1 year from 1995 to 1996 due to 800,000 new settlers.

Proposal and approval of infrastructure development projects and the status of wildlife and the ecosystem were the most frequently reported themes (26% of news items) from SGNP as revealed by the media content analysis (Fig. 11.3). Linear development projects such as freight corridors, roads and tunnels, bullet train projects and the car shed for metro projects in Aarey forests and consequent conflicts between environmentalists and government agencies have been reported. Encroachments by slums, restaurants, real estate, and large bungalows on the northern side have been damaging the park ecosystem (Zérah 2007).

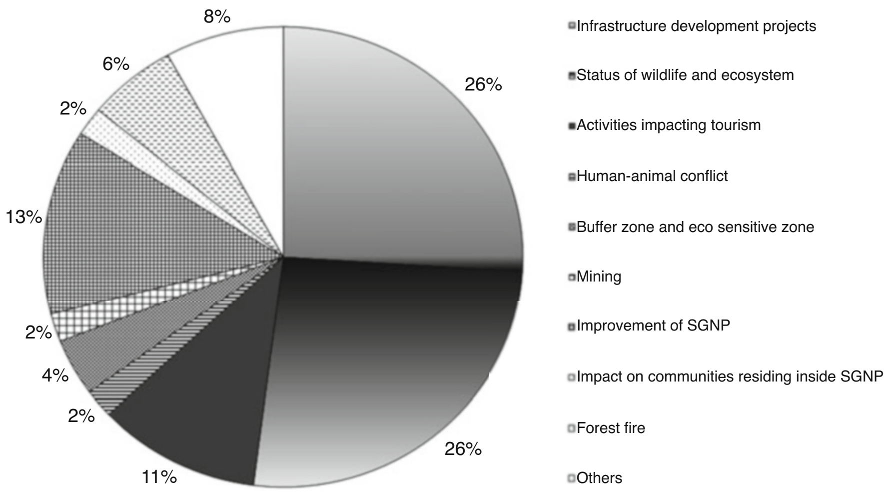


Fig. 11.3 Major themes of media reportage on SGNP

Mining and stone quarrying just outside the boundary of the park is a matter of concern for the biodiversity inside the park (Everard 2019), as corroborated by the content analysis also. Forest fires in the park in 2018 have also been reported in the content analysis. Indigenous community uses of resources, under the influence of changing economic motives, also have been exerting negative impacts on the ecosystem, for instance, *Ceropegia vincifolia,* a twiner that can be eaten like potato, is reported to be endangered because of extensive use by tribal community (Joshi et al. 2016).

11.3.1.3 Ecosystem Services and Disservices

SGNP is a source of provisioning services to local indigenous communities, supplying minor forest produce as well as supporting agriculture as a livelihood. However, the indigenous communities are now not permitted to use forest resources except dry wood, resulting in ecological alienation of the poor (Sen and Pattanaik 2015). Vihar and Tulsi lakes are major water sources for Mumbai and Thane districts and provide water security during delayed monsoons (Everard et al. 2020).

The forests provide regulating services of improving air quality, settling the particulate matter and breaking down aerial pollutants (Everard et al. 2020). Urban heat island is also mitigated by the forests that act as a natural air conditioner for the nearby areas, lowering the temperature by 3–5 °C and reducing electricity consumption in neighbouring residential areas (Everard 2019).

Habitat services of the park are well documented in research. SGNP is rich in the flora of high medicinal and economic value, and endangered species including *Ceropegia vincifolia, Flacourtia montana, Syzygium cumini, Ixora brachiata, Syzygium cumini*, and *Garcinia indica, Atalantia racemosa* and *Miliusa tomentosa* (Joshi et al. 2016). There is considerable media coverage on the status of the wildlife of SGNP, which was one of the most reported themes. News reports of a census conducted in 2011 showed a decline in the population of carnivores such as leopards and civet cats and an increase in herbivore population. An increase in the leopard population was reported from a census in 2018.

SGNP provides important cultural services as a recreational site visited by many local and foreign tourists (Narkar et al. 2017). The ancient Kanheri Buddhist Cave Complex housing more than 100 caves are of great spiritual and aesthetic value (SGNP 2017). Indigenous religious rituals, identity, social customs, aesthetics, language and dance forms such as ‘Tarpa’, ‘Pamru’ and ‘Gauri’ lend immense cultural heritage value (Sen and Pattanaik 2016). Tourism is vital income support to the indigenous communities and studies show that apart from economic benefits, social factors like the educational level of the local tourist guides also improved from participation in tourism activities (Sen and Pattanaik 2016). Activities to promote tourism is the fourth most frequently reported theme from SGNP.

As for ecosystem disservices, human-wildlife conflicts are rampant due to space constraints in the city and mushrooming of residential colonies near the boundary of the park that lacks proper fencing (Ranade et al. 2015). Leopards from the park have been attacking people within and around the boundary of the park (SGNP 2017). The practise of trapping and relocating leopards for reducing the pressure rather fuelled these conflicts as the relocated leopard is traumatised as well as the emptied location attracts the leopards who are unfamiliar with the location. Waste disposal near the park boundary attracts dogs and in turn the predators, increasing conflicts and mortality (Sequeira 2016). Media coverage reports that two leopards are being killed every year on roads along SGNP and highlights the services from leopards in controlling stray dogs and reducing rabies risks.

11.3.1.4 Governance Challenges and Implications

The park falls under the ambit of Maharashtra State Department of Forests but has considerable interference from the Archaeological Survey of India, the Bombay Natural History Society (BNHS) and other local Non-Governmental Organisations (NGOs). Land ownership is divided between the MCGM and even the military and the air force (Krichewsky et al. 2011). Out of the 103 km^2 area of the park, 83.6 km^2 which is 84% of the total area is classified as National Park and the remaining (mostly buffer zone in the periphery) is not classified officially (Zerah and Landy 2013; Edelblutte and Gunnell 2014). The park comes under different management authorities which makes a difference in the level of protection within the park as well (Edelblutte and Gunnell 2014).

Under the FRA, 2006, the tribal communities living in the park were given rights to their land and forest resources. However, the burden of proving the eligibility and residence duration has become a constraint and thus the conflict persists, as the ones who are not able to present documents are considered as encroachers and are rehabilitated (Sen and Pattanaik 2015). The tribal communities are still restricted by the forest officials and often portrayed as agents of forest degradation. Decision-making committee prescribed by the FRA is not functional on the ground as reported by the community (Sen and Pattanaik 2015). Since land and resources rights of the local communities are being ignored and real estate has been flourishing in the shadow of politics, the inequity in conservation is conspicuous.

11.3.2 Bannerghatta National Park

11.3.2.1 Social-Ecological Context

BNP is the largest natural ecosystem in the urban fringes of Bengaluru. The park was initially designed as a zoo with the intention of conservation and recreation and later became the Bannerghatta Biological Park (BBP) in 2002 under the administration of the Authority of Karnataka. The initial park area of 102.7 km^2 was expanded to 260 km^2 in 2011 (Ramachandra et al. 2016) with the addition of other reserve forests and a buffer zone of 5 km^2.

Dry deciduous and scrub forests dominate the rocky landscape of BNP. BNP is part of the Mysuru Elephant Reserve—the largest protected habitat for the Asian Elephant in Southeast Asia and is closely linked to other PAs like the Cauvery Wildlife Sanctuary in the south and Bandipur Tiger Reserve to the northeast (Mabeluanga et al. 2016; Ramachandra and Setturu 2019). BNP is home to diverse flora and fauna including sloth bears, 40 leopards (Rao 2019) and over 128 types of tree species, predominantly woody and scrub vegetation of *Acacia chundra*, *Anogeissus latifolia*, *Wrightia tinctoria*, etc. and medicinally important plants such as *Shorea roxburghii* and *Cassia fistula*. Plantations of Eucalyptus can be observed in and around the park as a result of reforestation programmes. There are 112 villages in the forest fringes and five within the park boundaries, where tribal communities such as the nomadic *HakkiPikki* tribe and the forest-dwelling *Iruliga* tribe are resettled (Singh 2008).

11.3.2.2 Land Use and Ecosystem Changes

Though the protected status has helped maintain more or less stable land cover in BNP, the surrounding landscapes have witnessed tremendous industrial, residential and tourism development (Jayaprakash and Hickey 2019). Even within the PA, the quality and nature of vegetation have changed. Suburban development and edge effects have resulted in the decline of the total forest density and the native scrub forest area at BNP (Adhikari et al. 2015). Due to the availability of suitable coarse granites and complex gneiss rock formations, intense mining can be observed around BNP (Varma et al. 2009). While extensive grazing, illegal sand and stone mining and unsustainable fuelwood extraction affected the forest fringes (Kakkar et al. 2018), the north and central parts of the PA experienced a considerable amount of deforestation. Unresolved land ownership, especially in the fringes, is one of the factors leading to deforestation in certain areas of the park (Nagendra et al. 2013; Adhikari et al. 2017). An increase in industrial units of stone crushers and glass, construction of arterial roads connecting several districts to the Bengaluru city have all contributed to land-use changes around the park (BDA 2017). Mining, and its impacts on wildlife movement and closure of some mining-related industries, was one of the most reported (25% of reports) themes from BNP in the media (Fig. 11.4).

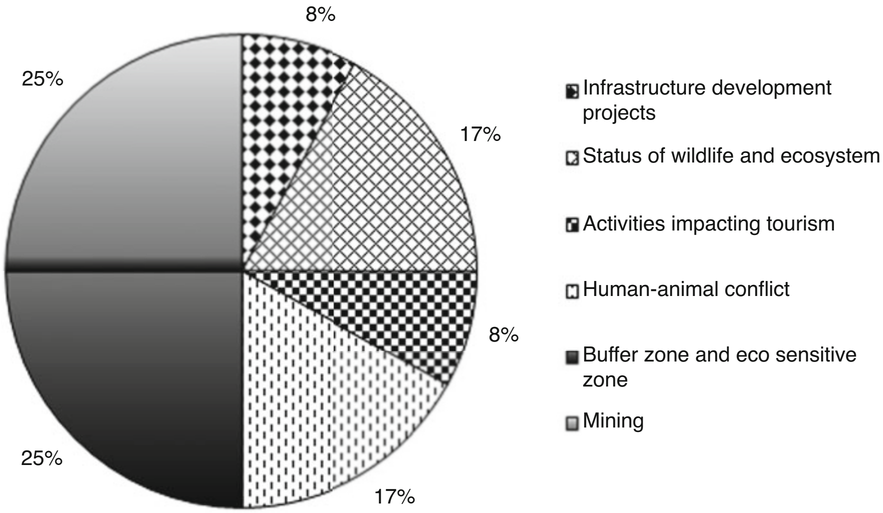


Fig. 11.4 Major themes of media reportage on BNP

Notification of an Eco-sensitive Zone (ESZ) of 268.9 km^2 across 13 adjoining villages with radii varying between 100 m to 1 km from the park boundary under Ministry of Environment, Forest and Climate Change (MoEFCC) rules in 2016 and later limitation of this area to 168 km^2 to facilitate developmental activities also received equal media attention. A proposal by the Forest Department for a night safari in the park was also reported in the media as being challenged in courts by environmentalists.

Land-use landcover change analysis of BNP with a 5 km buffer between 1973 to 2015 highlights severe vegetation cover loss from 85.78% to 66.37%. The area under moist deciduous forests has reduced from 26.1% to 13.8%, while infrastructure expansion resulted in an increase in built-up area from 0.4% in 1973 to 4.5% during this period. Area under both agriculture (29.6–37.5%) and horticulture (8.5–11%) have increased responding to growing demands from the city. The area under mining jumped from 0.1 to 1.3% during the same period. Future land-use projections indicate a continuous decline of forests to 35.59% by 2027 owing to further expansion in urban areas to 9.62% (Ramachandra and Setturu 2019).

Two striking land-use change trends are evident between 1973 and 2007—the transition from forest to non-forest area and the expansion of large-scale Eucalyptus and teak plantations that has altered the ecosystem. Areas that were previously used for subsistence agriculture of crops like millets and vegetables have seen a gradual shift towards tree plantations that feed into the local timber markets, especially in the eastern and western fringes of BNP, closer to the city of Bengaluru (Adhikari et al. 2017). Frequent crop raids by elephants have also influenced the shift in cropping patterns towards timber or coconut and palm plantations to reduce economic losses (Nagendra et al. 2013; Adhikari et al. 2015). Intensive agriculture and pastoral activity have led to a complete makeover of the BNP landscape from thorny grassland to deciduous forests.

11.3.2.3 Ecosystem Services and Disservices

BNP has a long history of human activity, supporting agriculture and collection of forest produce such as wild fruits, meat, manure, firewood, bamboo, lac, and honey (Varma et al. 2009). The original landscape of scrubland vegetation with scattered trees supported pastoralism to a large extent. But with the designation of PA, grazing and forest produce collection was banned, though grazing continues to happen in the park. Rivers Suvarnamukhi, Rayathmalaholé and Antharagange originate in BNP and join river Cauvery supporting agriculture, livestock grazing and fodder collection along their course. Along with providing critical habitat for diverse flora and fauna, BNP plays a major role in regulating Bengaluru's microclimate (Singh 2008) and provides watershed and pollination services critical to peri-urban agriculture (Patil et al. 2018). The status of wildlife in BNP assessed through the various census is the second most reported theme in the media, along with human-wildlife conflicts.

Cultural services of BNP include the recreational uses as an important tourist attraction and promotes awareness of *ex situ* conservation, environmental education and research opportunities. The economic value of ecosystem services from BNP was estimated to be INR 24.5 million, with recreational services emerging the most valuable, followed by carbon sequestration, soil erosion and provisioning services (Balasubramanian 2020).

The park is also a source of ecosystem disservices, especially human-wildlife conflict leading to crop depredation and loss of human life and property. The wild Asian elephant (*Elephas maximus*) and the wild boar (*Sus scrofa*) are major threats to farming in the peripheries. Mapping of damage showed that crop depredation was concentrated in the north-western and south-eastern regions that fall in the migratory routes for elephants (Bantalpad et al. 2017). Both food crops such as finger millet and cash crops such as sapota, mulberry and coconut were affected (Prasad et al. 2016). Local communities perceive deforestation around BNP as the prime cause of conflict. Changes in the behavioural patterns of elephants are also cited as reasons (Venkataramana et al. 2015). Fragmentation of the park from cultivation, mining and development projects contribute to increased incidence of conflict in villages situated closer to the elephant corridors (Varma et al. 2009). Barricading of the park boundaries by FD to prevent elephants from straying into human habitation was reported in the media. Adverse impacts of urban sprawl on wildlife in terms of road kills and the need for the realignment of roads were also reported in the media.

Overall, it could be deduced that the provisioning ecosystem services from the BNP landscape are on the decline following the declaration of PA status, while cultural services such as tourism and regulating services of biodiversity conservation are prioritised. It is to be noted that the cultural services are mostly enjoyed by urban residents and tourists from other places, while the regulating services provide global benefits, at the cost of excluding local users of provisioning services from the landscape.

11.3.2.4 Governance Challenges and Implications

As a national park, BNP is accorded the highest level of protection under the Wildlife Protection Act, 1972; however, the park has become an island amid a fast-urbanising landscape. The park is managed by the Karnataka Forest Department (KFD). The BBP under the Zoo Authority of Karnataka (ZAK) prioritises zoo management and recreational activities like wildlife safaris and tourism.

The northern and parts of the southern boundary of the park fall under the Bengaluru Development Authority (BDA) and Bengaluru Metropolitan Regional Development Authority (BMRDA). The park is geographically distributed under two districts—the eastern side is under Anekal Taluk of Bengaluru urban district and the western side under Kanakapura Taluk of Ramanagara district, each with its own Local Planning Authority (Patil and Raj 2019). Institutional complexities, overlapping jurisdictions of decision-making agencies and competing claims on land lead to conflicting management decisions. Studies also note that traditional caste-based institutions further complicate the management by influencing resource access and usage rights (Jayaprakash and Hickey 2019).

The denotification of the ESZ of BNP is an instance of development priorities undermining the conservation mandate, showing the inability of institutions to pre-empt harmful land-use changes. Around 30% of the original ESZ of 268.9 km^2 declared vide a MoEFCC notification to regulate land-use activities was later denotified by the Karnataka Government to make way for construction projects, highways and quarrying (Rao 2019). At the same time, the land title claims of traditional forest-dwelling communities such as *Iruligas* under the Forest Rights Act, 2006 (FRA) are not being recognised citing conservation needs, raising questions of equity and social justice.

Policy gaps are also evident in the response to human-wildlife conflicts. The mitigation is mostly focused on paying compensation and ‘attempting to manage wildlife menace’ and suggestions to ‘close down all corridors to avoid stray elephants’ as mitigation measures. The policy suggestions also include a 50% subsidy to farmers to put up solar fencing and suggestions for a shift in cropping patterns in the surrounding villages to grow chilly, tobacco and oilseeds etc. that are supposedly avoided by elephants. But the reports are not substantiated by studies that measure the effectiveness of these measures (Manjunatha 2016).

The Revised Master Plan (RMP) for Bengaluru, 2031 (BDA 2017) is guided by the Bannerghatta Forest and ESZ, where it proposed to retain all approved existing developments and promote eco-tourism activities within ESZ and retain the areas outside ESZ as Agriculture Zone. RMP2031 proposes improved connectivity through the development of village roads and bus stations, development of parks, lake rejuvenation, restoration of quarries adjoining forest boundaries as village forests etc. while claiming to protect the ESZ. The Working Plan for Bengaluru Urban Forest Division (2002–2012) states that lack of data for decision-making, and lack of updates of land record are major challenges in protecting green spaces in Bengaluru. The Karnataka State Tree Cover Enhancement Policy of 2016 has set a goal of 33% land for statewide tree cover, but in Bengaluru, there is no land use-based target for forestry. At the municipal corporation level, forestry targets are set in terms of the number of saplings planted, rather than land-use goals (Bengaluru Political Action Committee 2019).

11.4 Discussion

The comparison between the two selected protected forests (Table 11.1) reveals interesting trends of changes triggered by urbanisation in peri-urban green spaces.

Table 11.1 Comparison of transformations in socio-ecological features of the selected PAs

Feature	SGNP	BNP
Area	Total park area increased from 20.26 to 103 km^2 through land acquisition	Total park area expanded from 102.7 to 260 km^2 by adding neighbouring reserve forests
Forest/ ecosystem type	Mountainous with semi-evergreen and mixed deciduous forest, littoral swamps and mangrove vegetation	Rocky landscape with scrub and dry deciduous forests and grasslands in dry agroclimatic zone
Land use	Increase in the extent of forest cover by acquiring new land Decrease in natural mangrove areas, agricultural land and water bodies	Change from forest to non-forest area, expansion of large-scale Eucalyptus and teak plantations Decrease in areas under deciduous and the native scrub vegetation Land conversions for development, increase in agricultural and horticultural areas and mining activities in surroundings
Ecosystem services and disservices	Provisional services are declining as local use of the resources of the park is restricted, while cultural and regulatory services are prioritised. Human-wildlife conflict increasing due to the increased proximity between residential areas and the park boundary	Decreasing salience of provisional services and greater emphasis on cultural and regulatory services. Increasing human-wildlife conflict due to mining and agricultural intensification along wildlife corridors
Governance, institutions and stakeholders	Governance getting complex as park management and land ownership involves different authorities such as FD, Mumbai Municipal Corporation and even the armed forces. Other stakeholders include the Archaeological Survey of India, the BNHS and local NGOs. Indigenous communities are marginalised due to non-implementation of FRA, 2006	Overlapping agencies for park management such as FD, ZAK, Bengaluru Development Authority, Bengaluru Metropolitan Regional Development Authority, Local Planning authorities of Kanakpura and Anekal. Other stakeholders include several NGOs in addition to corporates like BIOCON engaged in CSR initiatives. Traditional caste hierarchies also influence resource use Land claims of indigenous communities still not recognised

Despite the differences in the size of the park and ecological features, there is considerable similarity in the trends of transformations in the two. In both, the cases area of the park has expanded, but the quality of the ecosystem has declined owing to urbanisation-induced pressures such as developmental projects, changing nature of agriculture in the peripheries to grow produce for urban consumption along with monoculture plantation programmes for reforestation. Under the influence of urban growth, the cultural ecosystem service uses of urban dwellers and tourists are prioritised, while traditional forest dwellers are denied access to resources citing conservation objectives. At the same time, forest cover diversion and reduction of ESZ—the transitional space to cushion the PA against destructive activities—are allowed to facilitate urban development and tourism activities that cater to the recreational needs of urban crowd and revenue generation motives of the state resulting in a skewed distribution of the burdens and benefits of conservation. Urbanisation thus accentuates the already existing in equity in conservation. The complexity of governance of PAs can be attributed to the multiple parastatal urban governance bodies that has become a defining feature of globalised megacities.

The media content analysis also reflects the threats to the park ecosystems from urban development activities. The most frequent themes varied between the two PAs; in the media reportage from SGNP, infrastructure development projects leading to forest diversion and the status of wildlife are the most popular themes, while in BNP mining and issues with the ESZ are the most important themes. Though BNP is the larger among the two, SGNP had a higher number of news items on the park in the period analysed, mostly due to a large number of reports on multiple infrastructure projects through the PA and good media coverage on the status of animal populations and the ecosystem. Mining and human-wildlife conflicts were not prominently reported from SGNP in comparison to BNP. It is also important to note that issues of indigenous communities such as non-allocation of land titles under FRA did not receive any media attention in both cases, again an indication of the inequity in conservation.

11.5 The Way Ahead

While it is impossible to halt or slow down urbanisation, there is an urgent need to evaluate and improve management efforts for critical urban green infrastructure including nature reserves. It is crucial to conserve nature reserves, especially in cities with dwindling green areas, recognising the role of urbanisation in reshaping the social-ecological dynamics around green spaces often leading to marginalisation of communities whose livelihoods traditionally depend on local ecosystems. Stressors of urban origin are not only direct such as urban development projects leading to forest conversion, but could also be indirect, for instance, the demand from the city for certain agricultural commodities leading to shifts in cropping practices that intensifies human-animal conflicts in peripheries. Forest and biodiversity conservation in urban landscapes will be successful, only when such pressures of diverse nature are identified and mitigated.

It is important for urban planning to be cognizant of integrating nature reserves within the urban fabric to ensure sustainable cities. The concept of Comprehensive Design Districts (CDD) is proposed for zoning around the national park to create zones with low to high intensity of development, namely, i) ecologically sensitive district, ii) culturally rich district, iii) institutional district, iv) movement districts to safeguard the green areas and water bodies, and formulation of guidelines for each zone (Patil and Raj 2019). Multisectoral decision-making reconciling competing claims of stakeholders and adaptive management processes should be institutionalised for effective urban nature conservation. There is undoubtedly a growing need for managing green infrastructure including nature reserves as 'commons' rather than fenced spaces excluding local users and livelihoods if resilient and equitable urban cities are to be fostered.

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Mapping the Extent of Invasive Species: An Assessment Based on High-Resolution Data for Selected Species in Parts of Eastern Himalaya in Sikkim

12

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Abstract

Invasive species have negatively affected almost all types of ecosystems on earth by eliminating native species, predation, being the vector of pathogens, hybridization, and facilitation of ecosystem process with effecting nutrient cycles, air and water levels (CBD 2006). Mapping of the invasive species in the forest ecosystem generally involves a detailed, scientific field survey to understand their distribution across slopes, aspects, elevations, various land uses and land covers, as well as temperature and rainfall regimes. In the present study, based on the infestation in the eastern Himalayan state of Sikkim, we have selected species like *Chromolaena odorata*, *Lantana camara*, and *Ageratum conyzoides*. We used two different approaches for the mapping – one was a feature space-based approach applied for *Chromolaena odorata* and *Lantana camara* as it is a nonparametric classifier that differentiates and divides the classes by determining the boundaries in feature space and maximizes the margin between classes (Keuchela et al. Remote Sensing of Environment 86:530–541, 2003). The second approach was grey-level co-occurrence texture measures to see the effect of textures in case of mapping of *Ageratum conyzoides* because of the presence of this species concentrated mostly around the disturbed habitats such as agricultural, fallow and abandoned land. The validated results show an overall accuracy of the classification as 86.76% with kappa statistics—0.72, 0.71, and 0.68 for *Chromolaena odorata*, *Lantana camara*, and *Ageratum coyzoides*, respectively. These results demonstrate the suitability of red edge band of WorldView-2 images

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to discriminate invasive species in mixed vegetation that can assist in the management of infestation in the high-altitude region.

Keywords

Invasive species · Grey-level co-occurrence · WorldView-2 · Edge density analysis · Red edge band

12.1 Introduction

Invasive species have posed a severe threat to biodiversity, food security, human health, trade, transport, and economic development (Czech and Krausman 1997); (Wilcove and Chen 1988); (Mooney and Cleland 2001); (Pimentel et al. 2005). Biological invasions have been identified as a major non-climatic driver of global change (Chown et al. 2015) and are supposed to be the most arduous threats to the ecosystem and human society. The damage caused in native species extinctions (Drake et al. 1989), biodiversity reduction (Mooney and Hobbs 2000), ecosystem services, and aesthetics is much more than the estimated monetary expenditure associated with management. In India around 18% of the flora comprises alien invasive species, of which 15% are of European and central Asian origin, 30% are from Asia, and 55% from America (Nayar 1977). Excepting high-altitude areas, nearly two million hectares of area are covered by invasive species (Aneja et al. 1993). *Lantana camara*, a native species of South, Central America and the Caribbean islands (Baars 2002; Day et al. 2003), has become a noxious weed in India and affecting the forest ecosystem and causing loss of biodiversity to an alarming extent (Sharma and Raghubanshi 2006; Prasad and Singh 2007; Sahu and Singh 2008; Babu et al. 2009).

Biological invasions can affect ecosystems across a broad spectrum of bioclimatic conditions. Therefore, information on invasive species' spatial distribution is critical in planning for their management and control. Remote Sensing and Geographic Information technologies—an important tool for large-scale ecological studies from the past three decades—offer potentially valuable tools for mapping and monitoring invasive species and provides information on areas susceptible to potential invasions (Padalia et al. 2014). Remote sensing, coupled with field survey, has been used over time to map the spatial extent of invasives (Tueller 1982). Studies show (Carson et al. 1995; Lass et al. 1996; Glenn et al. 2005; Joshi 2006) that high spatial and spectral resolution (hyperspectral) satellite data is more useful for mapping the extent of invasion. Capabilities of IKONOS 4 m and ASTER 15 m (Jakubauskas et al. 2000 and Chandra Kishore, et al. 2020) NOAA AVHRR data (1 km resolution) (Bradley and Mustard 2005) IRS P6 LISS-IV and Cartosat-1 merged products (Kimothi et al. 2010) were used to monitor the invasion of water hyacinth, *Bromus tectorum*, and *L. camara* respectively. Further (Jakubauskas et al. 2000) have used hyperspectral imagery for the mapping of invasive species. Due to its higher number of band discretization, it helps in vegetation mapping at different taxonomic levels. In the present study, high-resolution data capabilities of WorldView-2 (2 m resolution) were used to map the invasive species' infestation through its band discretization.

12.2 Study Area

South Sikkim district in Sikkim (Fig. 12.1), a mountainous state lying in Eastern Himalaya with a geographical area of 7096 km^2, was selected for the present study owing to heavy infestation of invasives in this region. The elevation range of the district is 400–2000 m above mean sea level. The district also has the highest forest cover (76.13%) in Sikkim regarding the total geographical area (ISFR 2015). Major Champion and Seth (1968) forest types reported in South Sikkim district are (1) East Himalayan Sal (3C/C1a), (2) East Himalayan Moist Mixed Deciduous (3C/C3b), (3) East Himalayan Subtropical Wet Hill Forest (8B/C1), (4) Buk Oak Forest (11B/C1b), (5) East Himalayan Mixed Coniferous Forest (12/C3a), (6) East Himalayan Sub-alpine Birch/Fir Forest (14/C2), (7) Rhododendron Scrub Forest (15/C1), (8) Dwarf Rhododendron Scrub (15/E1) and (9) Dwarf Juniper Scrub (15/E2) (ISFR 2015).

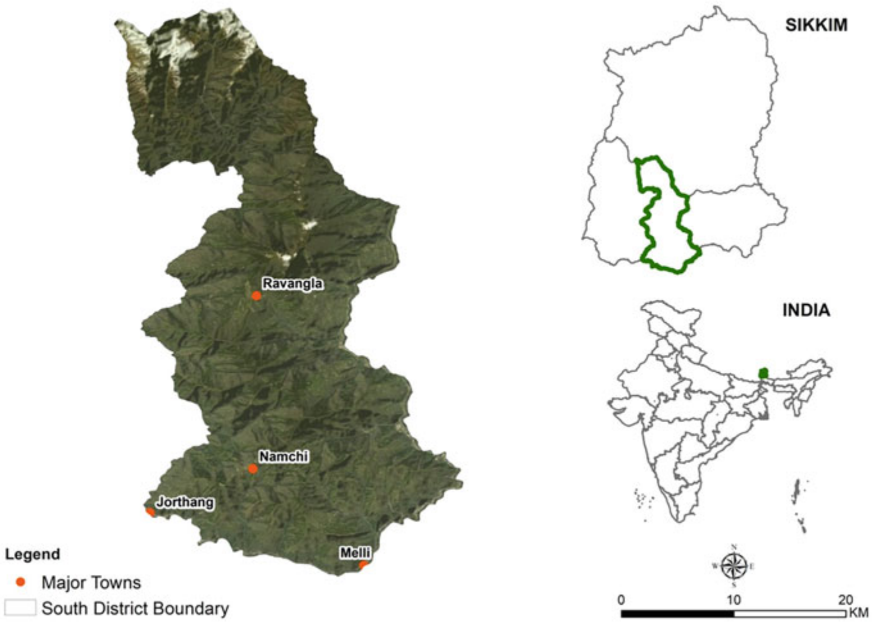

Fig. 12.1 Location of the study area

12.3 Materials and Methodology

12.3.1 Field-Based Assessment

The approach in this study included review and evaluation of various scientific literature and biodiversity assessment reports to identify and summarize the information about occurrence and distribution of different invasives in the study area. A preliminary survey was carried out to gather training sets for summarized information on the species. The presence of several invasive species was listed out in the survey. A listing matrix was prepared using current status, geographical presence, biodiversity, current management approach, forest type, and altitude range to map the species. To prepare the prioritization matrix, listed invasives were given a value between 1 and 5 for the identified parameters according to their invasion potential. Based on the analysis of the prioritization matrix, *L. camara, C. odorata, A. conyzoides, A. adenophorum* and *T. diversifolia* were the main invasive species and were chosen for the study (Fig 12.2a–c—Field photographs and its spectral response on FCC).

12.3.2 Remote Sensing-Based Assessment

Mapping of the invasive species generally involves an elaborate, scientific field survey of invasives to understand their distribution across slopes, aspects, elevations, various land uses and land covers as well as temperature and rainfall regimes. In the present study, we used WorldView-2 data resampled at 2 m resolution to identify *L. camara, C. odorata, A. conyzoides*, and *T. diversifolia*. Since invasives colonize diverse habitats and have a specific growth pattern, our approach for identification and mapping was species-specific, based on the habitat criteria and ancillary information derived from the field – detailed under the geospatial approach of the mapping of invasive species in Fig. 12.3. The infestation of *Lantana camara* and *Chromolaena odorata* were mostly noticed along the roadside, on fallow lands, and on or near the degraded and open forest areas in the South District of Sikkim. Altitude has been taken as one of the criteria for identifying and mapping *L. camara* (found up to 1800 m above mean sea level) and *C. odorata* (limited up to 1600 m above mean sea level). Firstly, to study the infestation extent, linear stretching was performed to contrast high-resolution images of WorldView-2 data. In general, the areas infested by *L. camara* and *C. odorata* appeared brighter on the image. Hence, the raw satellite image was first filtered using a 3×3 kernel high-pass filter that extracted the high-frequency components. A scaled version of the high-pass filter output was then added to the original image for producing a sharpened image.

The enhanced image was then classified using feature space-based image classification, a simple classification that quickly transforms a three-band image into a single-band pseudo-colour image. The algorithm plots the LUT (Look Up Table) values of all pixels in three-dimensional feature space and then partitions this space

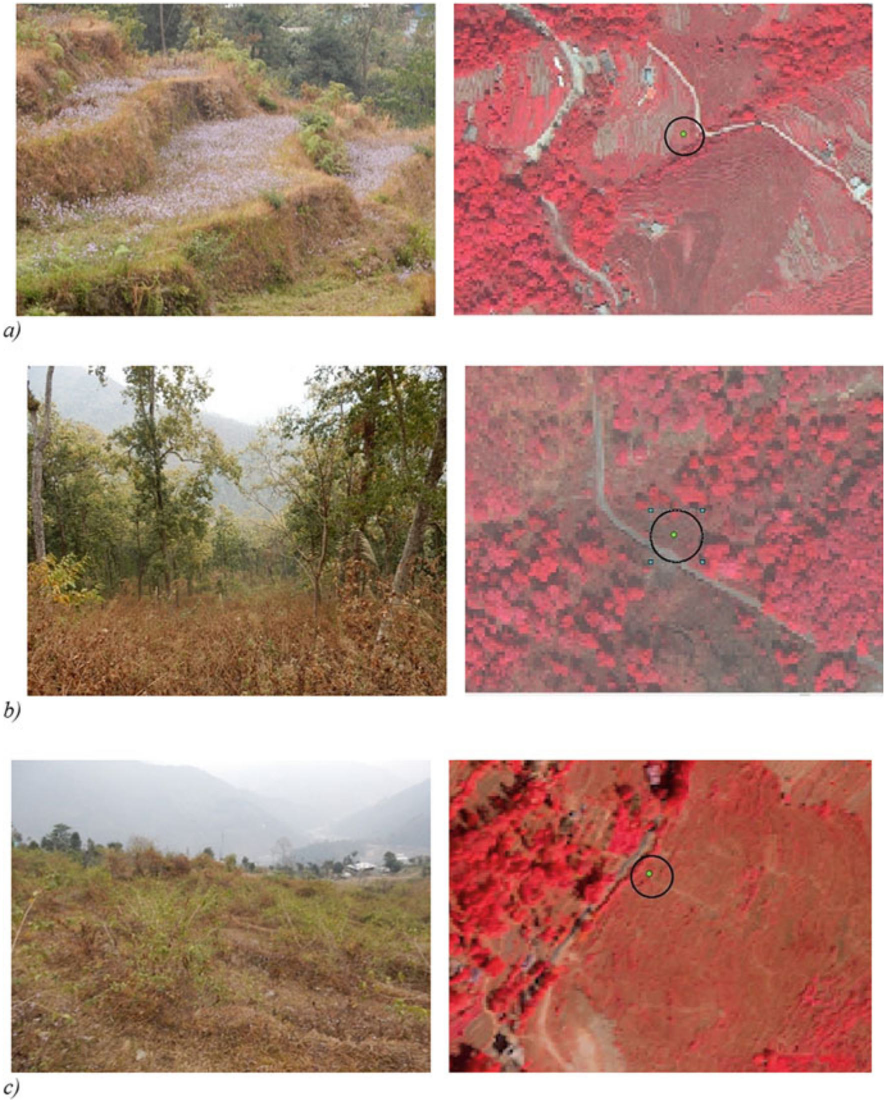

Fig. 12.2 Physical extent of invasive species (**a**–**c**). (**a**) *Ageratum conyzoides* infestation on ground and as captured in WorldView-2 data. (**b**) *Chromolaena odorata* infestation on ground and as captured in WorldView-2 data. (**c**) *Lantana camara* infestation on ground and as captured in WorldView-2 data

into clusters on a grid. Each of these clusters was then sliced into a class in the thematic layer. A slightly different approach was adopted to map *A. conyzoides*, a species of disturbed habitats such as agricultural fallows and abandoned land. Grey-level co-occurrence texture measures were generated to see the effect of textures.

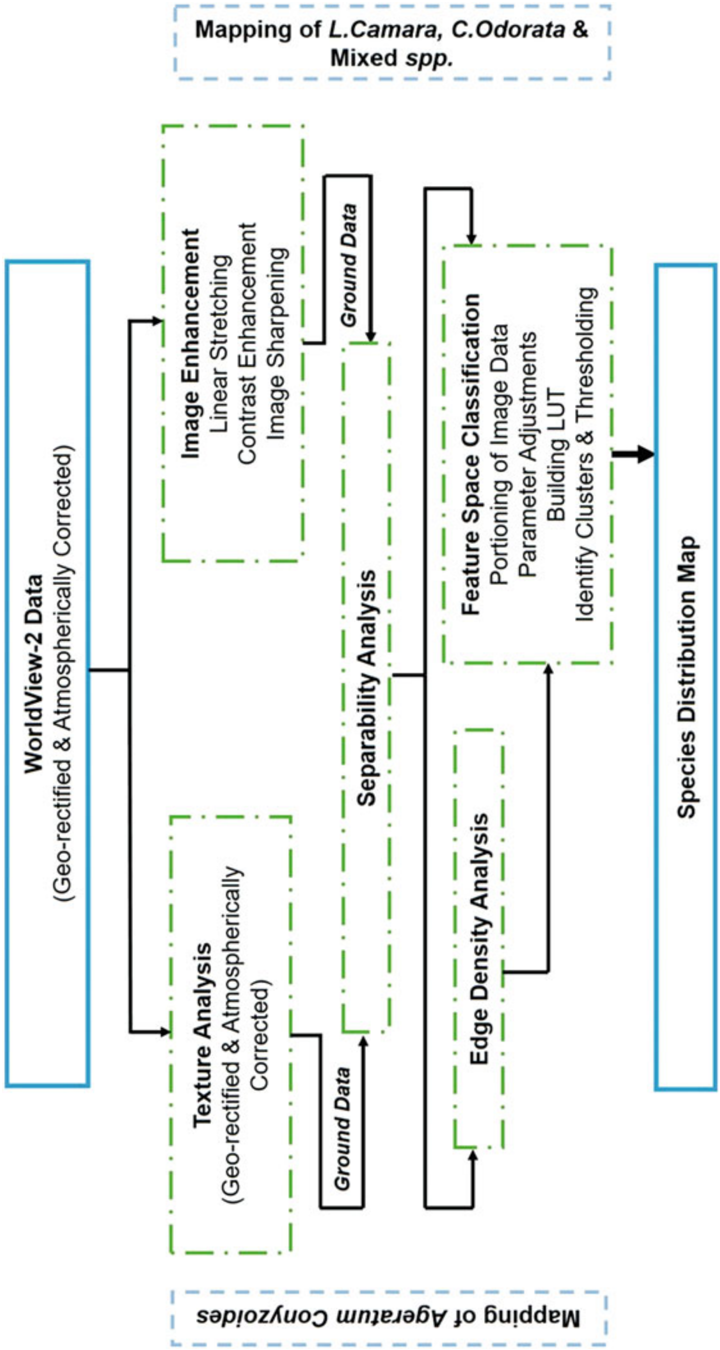

Fig. 12.3 Methodology flowchart for the mapping of invasive species

The red edge band was used to generate the GLCM measures, and texture information was collected using training sets.

Further, edge density analysis through high-pass filtering was performed to segregate the uninfested areas, namely, the agriculture bunds, where *A. conyzoides* was mostly found. This technique uses a high-pass filter to get the edges by thresholding the values based on the histogram interpretation. Vegetation indices were also generated using red edge and blue band and tested for the separability analysis of the uninfested forests and the infested forest and non-forest areas. This information was ably used to improve the segregation of *A. conyzoides* with the mixed healthy forest patches. The LUT-based advanced RGB clustering followed this step to classify the final *A. conyzoides*-infested areas. Finally, the mean and standard deviation of digital number values were calculated to determine their spectral separability. Separate mapping of the two species (*Tithonia diversifolia* and *Chromolaena odorata*) was not possible due to the very high overlap in spectral signatures. Hence, at those places, a mixed-species class was introduced wherever spectral separability was low (Fig. 12.4).

12.4 Results and Discussion

The output shows *C. odorata* occupying maximum area (1336.48 ha) in South District of Sikkim, followed by *L. camara* (373.59 ha) and *A. conyzoides* (195.09 ha), while mixed species cover an area of 95.09 ha (Table 12.1). Most of the species were found to be light-demanding with the major infestation in open canopy except *Eupatorium adenophora*, which was found in moist areas and shadow regions. Due to high sun layover in the entire South Sikkim, it was difficult to spectrally delineate *E. adenophora*. The lower altitudes forest (>500 m) were predominantly infested with *L. camara* and *C. odorata*, comprising of land use like degraded forest due to developmental and anthropogenic activities and barren land. *A. conyzoides* were mostly found along the bunds of dry uncultivated lands and grazing lands.

The field survey points were further analysed, and random field points were generated across the district to validate the thematic map showing the invasives' distribution in the study area. A thematic correction was carried out to address the mismatch with more than 10% error during validation, and a resultant output map, with 90% accuracy was generated. During the field survey, few patches of mixed invasive species were spotted with the infestation, mainly of *T. diversifolia* and *C. odorata,* considering the similar habitat on which these two species proliferate.

To further validate the results, the spectral comparison analysis for the two species was done to check their spectral separability. The results showed a very high overlap of spectral signatures as their mean values were also very close (Fig. 12.5). Hence, a separate class was mapped as a mixed class wherever spectral separability was low. This gives an overall accuracy of 86.76% with kappa statistics—0.72, 0.71, and 0.68 for *Chromolaena odorata*, *Lantana camara*, and *Ageratum coyzoides*, respectively.

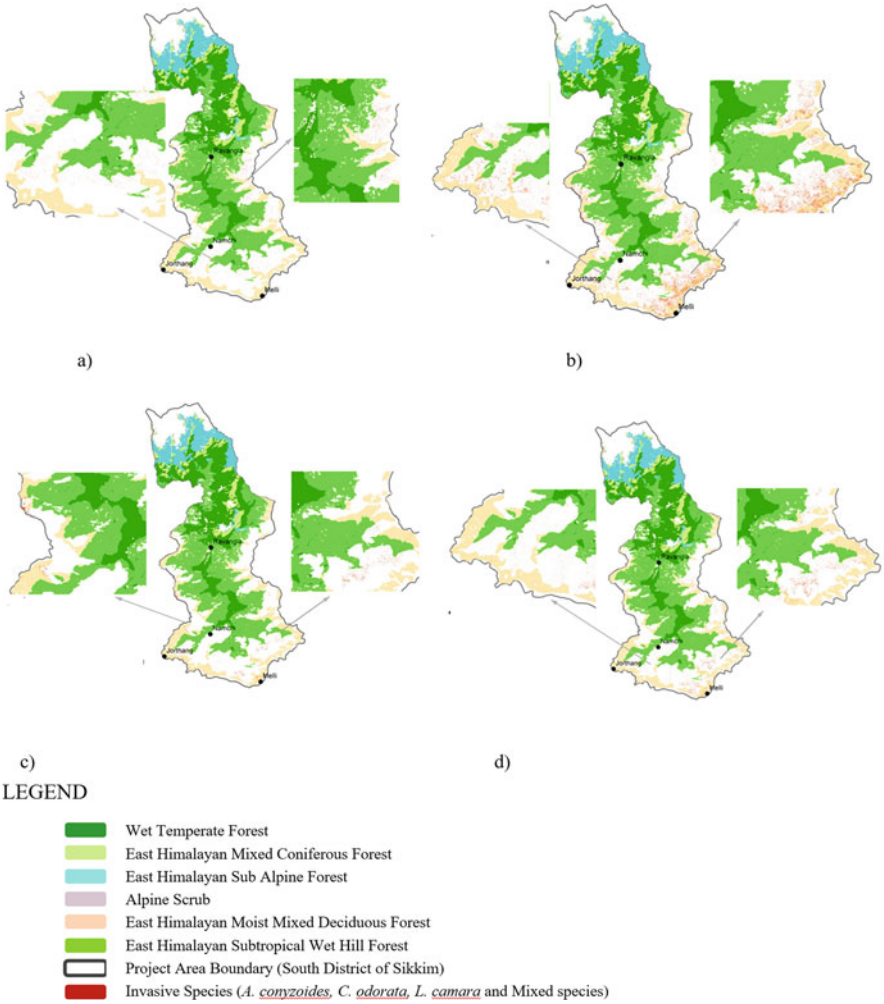

Fig. 12.4 Output of the infestation by various species in the forest. (**a**) Infestation of *Ageratum conyzoides*. (**b**) Infestation of *Chromolaena odorata*. (**c**) Infestation of *Lantana camara*. (**d**) Infestation of mixed species

12.5 Conclusion

In most cases, observing invasive plant species requires data collected from sensors pushing the limits of at least one type of resolution (spatial, temporal, or spectral resolution) as these species' profiles in the present case were quite similar to those of native plants, from a remote-sensing perspective. Integration of pixel-based classification with ecological setting information of the species has enhanced the species'

Table 12.1 Distribution (area in ha) of invasive species in different land use land cover

Land use land cover	*C. odorata*	*L. camara*	*A. conyzoides*	Mixed spp.
Mixed Moist Deciduous Forest	231.06	50.75	0.00	16.43
Wet Temperate Forest	0.63	1.10	0.00	0.48
Subtropical Wet Hill Forest	80.43	34.37	0.00	3.81
Coniferous Forest	0.00	0.00	0.00	0.00
Sub-alpine Forest	0.00	0.00	0.00	0.00
Cropland	596.13	202.96	194.89	40.27
Water bodies	0.17	0.17	0.00	0.01
Grassland	363.84	71.36	0.00	27.31
Other land	61.75	11.99	0.00	6.31
Settlements	2.41	0.88	0.20	0.48
Total	**1336.48**	**373.59**	**195.09**	**95.09**

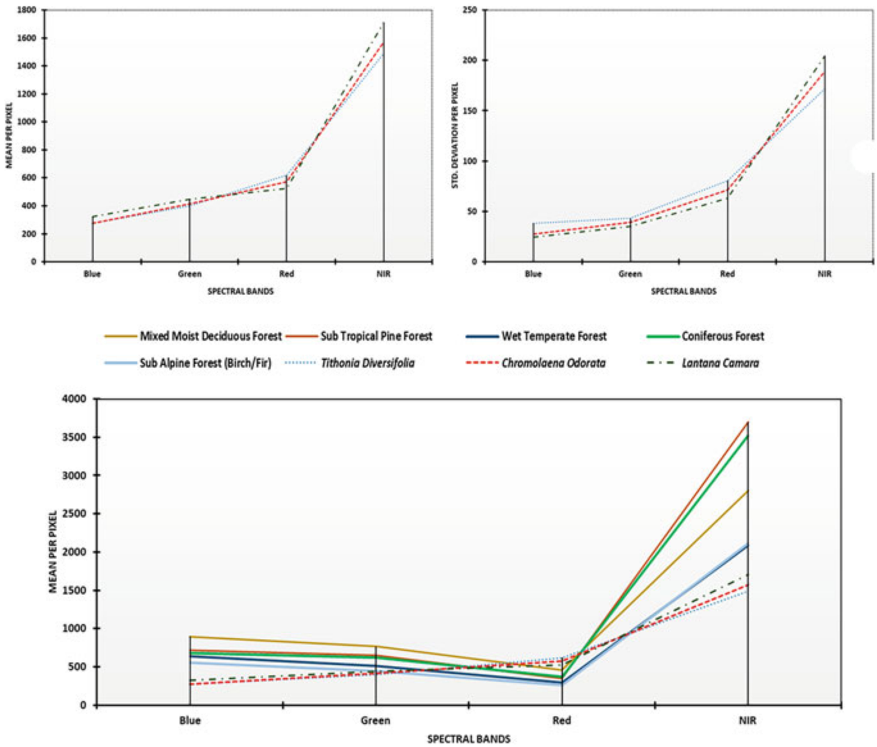

Fig. 12.5 A comparison of mean pixel values of *T. diversifolia, C. odorata, L. camara* and different land use classes in different bands

mapping accuracy. The spatio-temporal variation in the species' phenological characteristics and the surrounding vegetation play an essential role in detecting species under vegetation cover. The satellite datasets used in the study were temporally consistent with the field survey conducted in February. This leaf off-season has helped map the extent of species under open canopy patches of mixed moist deciduous forests. The high spatial and spectral resolution and improved geospatial positioning capabilities of WorldView-2 had provided an effective means of discriminating invasive species with native vegetation types. The altitudinal gradient is also one of the deciding factors for variations in the species composition and vegetation pattern.

Further, in terms of infestation in forest land, mixed moist deciduous was the most affected at a lower elevation with floristic composition, mainly of *Shorea robusta* (Sal) and *Tectona grandis* (Teak) species. Similarly, the spread pattern of invasive species, as in most cases in other parts of India, was characteristic of degraded and abandoned land use. In such cases, the potential of very high-resolution data supported with topographic information can significantly reduce uncertainties for plant species mapping and assessment.

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Part III

Insights to Innovations

Groundwater-Dependent Vegetation to Address the Loss of Ecosystems Dependent on Groundwater Resources

13

Jayshree Shukla, Shalini Dhyani, Paras Pujari, and Parikshit Verma

Abstract

Groundwater supports the sustenance of major ecosystem functions including maintenance of native vegetation. Water availability to the groundwater-dependent ecosystems is directly influenced by the water table depth. Overexploitation and overextraction of groundwater resources have led to water scarcity and impending water crises all across the globe. In the present decade, much focus has been given to the rapidly depleting water resources and their impact on future generations. But the impact of the water table dropdown on the ecosystems it supports has been overshadowed by prioritizing human water needs and ways to replenish the water sources to fulfil population demand. Groundwater-dependent ecosystems support a wide range of ecosystem services and are critical habitats that need to be included in the watershed-level policies and water resources management initiatives, in order to build a sustainable ecosystem with the precise allocation of water resources. The present chapter discusses the Groundwater-Dependent Ecosystems (GDE) and their classification, briefly discussing the methods for their identification, along with the global advances in GDEs mapping and groundwater allocation trends. The chapter highlights the need for GDE assessment especially for developing and underdeveloped countries that are currently facing water stress.

Keywords

Vegetation water demand · Water stress · Ecohydrology · Stable isotopes · Remote sensing

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13.1 Introduction

Freshwater makes up just 2.5% of the Earth's water volume, while two-thirds of that freshwater is trapped as glacial or permafrost ice (Margat and Van der Gun 2013). Groundwater (GW) accounts for 96.3% of all unfrozen freshwater on the planet (Downing 2014; Aldous and Gannett 2021) and is the most exploited raw material on the planet, with extraction rates up to 982 km^3/year (Villholth and Giordano 2007). In most regions of the world, groundwater resources are at danger of depletion because, as surface water supplies are getting scarce and polluted, and the practicality of capturing and storing these resources are rapidly declining, this has resulted in using groundwater as the next-generation resource (Cantonati et al. 2020). For two reasons, groundwater as a source for plants is not restricted to arid and semiarid places; it is probably more important in a seasonal environment with abundant wet season rain followed by a distinct dry season. First, during the rainy season, the aquifers are sufficiently refilled. Second, increased yearly rainfall can support better productivity (e.g. more and larger trees), which necessitates more water; higher resource demands and greater capacity to fix and distribute carbon may push and enable plants to grow deeper roots to access deeper resources (Fan 2015).

Groundwater-dependent ecosystems (GDEs) are key biological aspects of the landscape that rely on groundwater to maintain their ecological function, health, and vigour (Eamus 2009), and they provide unique habitats for a variety of terrestrial flora and fauna species. Numerous wetlands and seasonal-water habitats expose their need on groundwater sources for riparian flow, river base flow, and appropriate moisture content in soil-root and unsaturated zones in the absence of precipitation (Paz et al. 2017). Aquifers, caverns, lacustrine wetlands (e.g. lakes), palustrine wetlands (e.g. swamps), riverine wetlands (e.g. rivers), and terrestrial vegetation are all examples of GDEs. The majority of GDE are now endangered by a confluence of global climatic variables that are extending drought spells, as well as local human-induced stressors including land-use changes and pollution (Eamus et al. 2016). Figure 13.1 shows the impact of groundwater pumping and overextraction of resources on the depending vegetation and different GDEs. The ecological and economic relevance of groundwater is becoming more widely recognized. However, understanding the relationship between groundwater and the ecosystems it supports remains a critical step in connecting human and biological water requirements (Krogulec 2018).

13.2 Ecohydrology

Ecohydrology as an interdisciplinary science involves the effects of hydrological processes on ecosystem structure and functions, along with biological activities on hydrological cycle parameters in dynamic settings (Bridgewater 2021). Ecohydrology was explicitly introduced at the International Conference on Water and Environment in 1992, despite the fact that interdisciplinary study between ecology and hydrology has a long history, such as forest hydrology and wetland

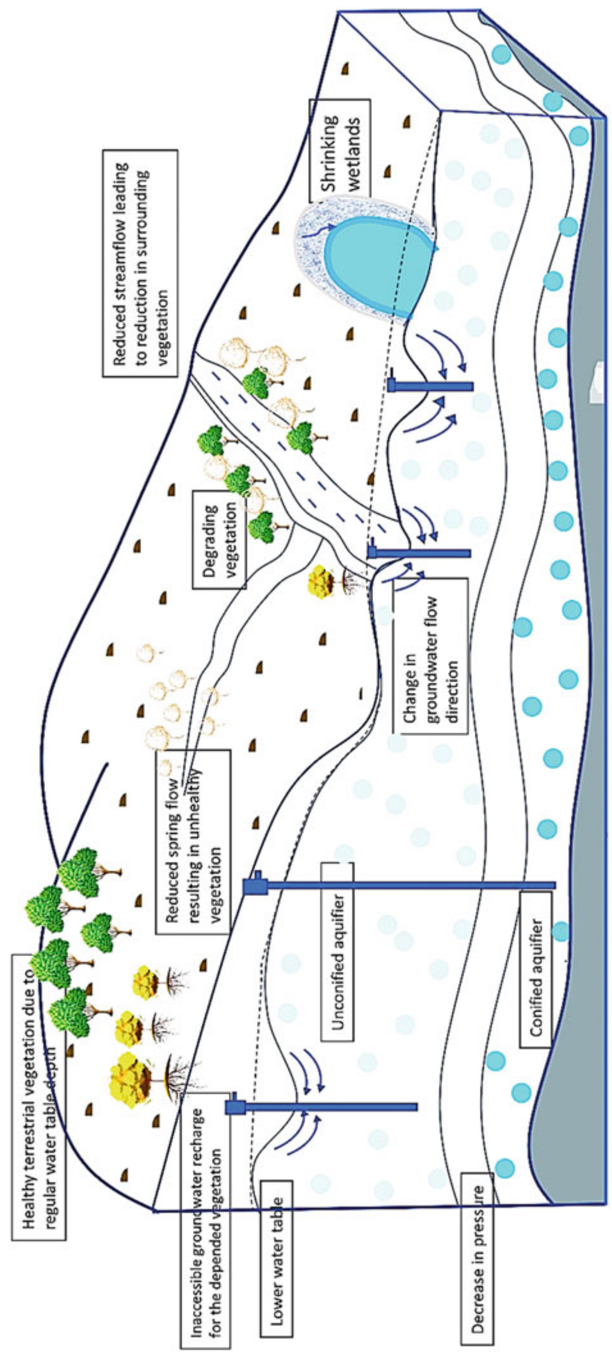

Fig. 13.1 Ecohydrology of groundwater-dependent ecosystems and the impact of overextraction and pumping on the surrounding vegetation

hydrology. Ecohydrological research has progressed from transitional zone wetland ecosystem studies to comprehensive investigations of numerous systems and freshwater resources, such as vegetations, rivers, lakes, and forests (Xia et al. 2021).

Ecohydrology can now contribute significantly in accomplishing the Sustainable Development Goals (SDGs), particularly in terms of Integrated Water Resources Management (IWRM). The use of ecohydrology concepts in IWRM provides a better understanding of the connections among water, biodiversity, and social well-being in watersheds. The integrated approach resolves one issue with the SDGs, that is, they have been presented in a 'silo' format, which implies that SDG 6 'clean water and sanitation" and SDG 15 'life on land' have little if any linkages (Bridgewater 2021).

WBSR – to identify the important elements: W for water, B for biodiversity, S for (ecosystem) Services, and R for resilience—was presented as an approach to ecohydrology by Zalewski 2014. He also points out that these factors are linked by three interrelated concepts: hydrological, ecological, and ecological engineering principles. The hydrological principle connects the measurement of hydrological processes to the measurement of ecosystem function at the basin scale, but the concept is scale-independent. The ecological engineering philosophy encourages humans to use ecosystem qualities, such as ecological and hydrological properties, as managing tools, particularly by developing and safe-keeping of wetlands. Understanding ecosystem shift is essential as per the ecological principle.

13.2.1 Nature-Based Solutions for Ecohydrology

The term Nature-Based solutions (NbS) used by the European Commission originated from the term natural solutions used by International Union for Conservation of Nature (IUCN) more than a decade ago as a means of bringing protected areas and species conservation measures into the center stage of biodiversity conservation (Maes and Jacobs 2017). The term is now adopted by IUCN as a medium to promote solutions provided by nature against climate extremities and other global challenges (IUCN 2012; Cohen-Shacham et al. 2016; Dhyani et al. 2020a, b). However, increasing research suggests that NbS are equipped to be used not just to deal with climatic adversities, but can also be benefitted from in the nexus of natural resources management in a broader scale (Eggermont et al. 2015; Dhyani et al. 2020a, b). Ecohydrology, which is in itself a multidimensional approach, can be amplified and reflected practically through nature-based solutions for various aquatic and ecological issues.

The application of NbS is not limited to specific ecosystems, but when it comes to aquatic and belowground interactions, ecohydrology can provide an evidence base for practical application of NbS and their inclusion in policy formation. In the rapidly changing world, to resolve known-unknown issues that are currently faced by humans, NbS are the key to achieve global sustainable goals (UN-SDGs) which can be strengthened through increasing research and understanding of ecohydrology principles (Bridgewater 2018).

13.3 Classification and Identification of GDEs

13.3.1 Classification

Hatton and Evans (Hatton et al. 1997) categorized the groundwater-dependent ecosystems for the first time in 1998 by recognizing five classes of GDE, namely, obligate GDEs which are entirely groundwater dependent and can lose their complete ecosystem structure and function even due to small changes in groundwater availability, highly water-dependent GDEs in which small to moderate changes in groundwater availability result in significant changes in ecosystem structure and function, proportionally dependent GDEs which do not exhibit the threshold-type responses of obligate or highly dependent GDEs, opportunistic GDEs which are facultative users of groundwater, that is, only in the condition of low surface water flow or droughts, and GDEs that only appear to be groundwater-dependent but are in fact entirely rain fed or dependent only on surface water flows. This classification lacks the accuracy in determination of the degree of dependency, and the presence or absence of threshold response is difficult to establish (Doody et al. 2017).

A simplified classification system by Eamus et al. (2006) categorizes GDEs in three classes:

1. Stygofauna habitats like aquifers and cave ecosystems along with hyporheic zones of floodplains and rivers (Humphreys 2006).
2. Surface groundwater expression–reliant ecosystems such as rivers, streams, wetlands, springs, and estuarine habitats.
3. Sub-surface groundwater expression–reliant ecosystems within its rooting depth (terrestrial vegetation (phreatophytes)).

13.3.2 Identification

Identification of groundwater-dependent ecosystems is the initial step towards their management. Locating different types of groundwater-dependent ecosystems is a tedious process and requires technical understanding and precision; it is also very time-consuming (Pérez Hoyos et al. 2016). Increasing research on GDEs have led to discovery of new approaches that can assist in better identification of the GDEs and are briefly discussed below.

13.3.2.1 Inference-Based Methods

Inference-based methods have been used by the farmers/landowners for a long time (Colvin et al. 2003). The basis of determination of GDEs depends upon the association between long periods of rainfall and droughts with consistent plant growth. If the soil water storage and water use rates by vegetation could be determined, then if the water use exceeds the soil water storage capacity, the utilization of groundwater by the vegetation becomes clear. Likewise, the vegetation water use in riparian and wetland ecosystems during the periods of drought is a parameter to confirm the dependence of vegetation on groundwater (Murray et al. 2003). During the period of low groundwater availability, if the vegetation continues to sustain without any harm in its ecological functionality, its dependence on the below groundwater is established (Eamus et al. 2006).

13.3.2.2 Stable Isotope Analysis

Stable isotope ratios of oxygen (O) and hydrogen (H) can be used as tracers to identify different water resources (Harris et al. 1999). These water sources are identified by a comparison between soil water and plant sap extracted from suberized stems using a process called cryogenic distillation and potential water sources through extraction from monitoring wells. The isotope ratio is then calculated relative to a standard water source and thus provides clear variation in the isotopic ratios of all sources (West et al. 2006). Stable isotopes of Carbon (C) have also been used for this process. The amount and duration of dependence of vegetation on groundwater can thus be analysed through temporal and spatial information on the water sources (Torres-García et al. 2021).

13.3.2.3 Hydrometric Technique: Water Table Depth

In dry and semi-arid environments, the obvious link between phreatophytes and GW depth and discharge has long been established (e.g. Nichols 1994; Aldous and Gannett 2021). Such links are less clear in humid climatic zones and have just lately been examined. Meteorological circumstances, plant type, soil factors, and water table depth all influence evapotranspiration (ETg) from groundwater. Various attempts to link ETg to the depth of the water table have shown that the deeper the water table, the less the groundwater input. Using hourly or more frequent measurements of groundwater levels in an observation well, the white approach has been the most consistently employed to estimate daily ETg (Orellana et al. 2012).

13.3.2.4 Temperature Variations

Numerous studies have attempted to measure temperature differences to better understand surface-groundwater exchange processes. Using temperature as a tracer in a series of approaches, including detecting groundwater movement near streams (Anderson 2005); estimating the flow and flux of groundwater discharge; locating steam inflows and outflows; and calculation of vertical water fluxes to evaluate natural interactions across riverbed sediments, has been a common approach (González-Pinzón et al. 2015).

13.3.2.5 Remote Sensing Tools

The adaption of remote sensing (RS) techniques is one of the most often utilized ways to regional GDE evaluation. Starting with early work on land cover mapping, RS has been used to track vegetation dynamics (Tucker et al. 1985). The successful use of RS data to the delineation of GDEs requires a thorough knowledge of the link between GDEs and groundwater systems, as well as their fingerprints in surface pictures that are geographically and/or temporally distinct from the surrounding areas. A number of RS applications to GDE analysis have looked at the properties of groundwater-dependent plants and wetlands/rivers that could be observable in remote sensing (Tweed et al. 2007). In the process of GDE mapping by remote sensing, the remotely sensed imagery is primarily used to extract information and provide explicit indicators that can help differentiate between the surrounding land cover classes and the potential GDEs. Image preprocessing (in order to increase the interpretability) and classification are primarily involved using the colour, tone, pattern and texture of the land cover (Perez Hoyos et al. 2015).Technologies like light detection and ranging (LIDAR), radar imagery, synthetic aperture radar (SAR), LANDSAT Thematic Mapper (TM) etc. are used for production of highly accurate digital elevation models, assessing impact of natural and anthropogenic disturbance, estimating evapotranspiration and water use, classification of successional stages of forest growth etc. in several studies (Hess et al. 2003; Lang et al. 2008; Hansen et al. 2009; Castañeda and Ducrot 2009; Matic et al. 2020; Huang et al. 2020).

13.4 Groundwater Management on Global Scale

Water-related legislation are written and interpreted in a variety of ways around the world to safeguard GDEs. Each country's overarching legal framework and constraints, as well as how current laws are applied and construed, set the course for policy choices and provide a local framework for protecting springs, seeps, and wetlands (Kreamer et al. 2015). Identification and protection of groundwater-dependent ecosystems has gained momentum on a global scale in past few years due to increasing research and real-time observations of drastically depleting water resources and their poor management, prevalent from many decades. Further studies on GDEs and their response to groundwater and climate variability have been outlined in Table 13.1.

Several countries have formulated laws and policies having direct links to the conservation of these resources and their ecosystems sustained by groundwater. However, each country differs in the enforcement of the law depending on regional and local challenges arising from their implementation and management differences.

13.4.1 USA

In the United States, the Clean Water Act (CWA)[1] provides some protection to the water quantity and quality that supports the GDEs which comes within the jurisdictional wetlands with no net-loss policy. However, the act only takes into account the wetlands that have surface water connections and controls the flow of pollutants in the surface waters such as streams, some wetlands and rivers. This leads to the geographically isolated wetlands with variety of ecosystem service provisions

[1] https://www.epa.gov/laws-regulations/summary-clean-water-act

Table 13.1 Impact of different drivers and indicators on groundwater and its associated ecosystems along with the response of dependent vegetation to groundwater variability

S. no.	Drivers/indicators	Impact on groundwater variability	Impact on vegetation	Reference
1.	Low rainfall, increased temperature	Reduction of groundwater recharge, increase in groundwater withdrawal rates	Increased groundwater dependence, detrimental effects of groundwater extraction on vegetation ecophysiology	(Chambers et al. 2013) Australia, Morsy et al. (2017) Kuwait, Antunes et al. (2018) Spain
2.	Groundwater recharge reduction due to climate change	Conversion of nested flow systems to single-flow cells	Changes in plant vigour, precipitation, groundwater depth and evaporative demand	(Havril et al. 2018) Hungary, (Huntington et al. 2016) United States
3.	Water table decline	Disappearing of wetlands and associated ecosystems	Decrease in leafing intensity with increasing plant height and water table depth. Decrease in transpiration rates (critical depth 3.6 and 2.0)	(Han and He 2020) China, (Wang et al. 2020a, b) China
4.	Changes in NDVI	Statistically significant changes in summer NDVI and groundwater level while moderate correlation was established between interannual summer NDVI and interannual water-year precipitation	– Decrease in depth to water (DT)T ($p < 0.05$) increase in NDVI ($p < 0.05$) – Vegetation primary productivity and groundwater depth are correlated in more than two thirds of the global vegetated area	(Huntington et al. 2016) United States, (Koirala et al. 2017) Global
5.	Changes in evapotranspiration rates	Decreasing groundwater contribution to evapotranspiration	– Higher ET in shallow water table crops than those from deeper water tables during the dry season transition. – Peak evapotranspiration	(Huang et al. 2016) China, (O'Connor et al. 2019) Brazil, (Lurtz et al. 2020) United States, (Zhang et al. 2020) Northern China (Sommer et al. 2016)

(continued)

Table 13.1 (continued)

S. no.	Drivers/indicators	Impact on groundwater variability	Impact on vegetation	Reference
			rates at groundwater depths <3 m, and evapotranspiration values significantly lower at depths greater than 3 m. – At DT > 1 m NDVI declines with increasing DT – At DT < 1 m veg growth is restricted. NDVI correlation coefficient ($p < 0.01$)	

throughout the country. State implementation of these policies has bridged this gap to a certain extent. The Endangered Species Act (ESA)[2] and the Safe Drinking Water Act[3] also provide protection to the GDEs to some extent where GDEs provide habitat to the listed species that rely on groundwater for some extent of their life and by taking into account the health of the aquifers for safe drinking water purposes. States like Michigan, Oregon (Dwire et al. 2018) and Florida have been working on protection of groundwater-dependent ecosystems setting an example for the country. The Michigan law clearly prohibits the resource withdrawal which might cross the threshold and cause adverse impact (changes in flow or water level causing alteration in the potential for supporting services provided by the ecosystem) on the water resource or the water-dependent ecosystems of the state. Michigan and Florida have the laws to protect certain GDEs that link with the instream flows and their associated biota but lack in protection of full suite of GDEs such as springs and wetlands. In Florida, the water law requires establishment of minimum flow and level of water bodies and also allows permit to only those parties that can demonstrate legal and beneficial water use. It also requires the assessment of impact of extraction on the dependent ecosystems including springs and wetlands (Kreamer et al. 2015).

[2] https://www.fws.gov/international/laws-treaties-agreements/us-conservation-laws/endangered-species-act.html

[3] https://www.epa.gov/sdwa

13.4.2 European Union

The European Union has developed certain policies such as the Water Framework Directive and the subsequent Groundwater Directive that included specific criteria to be met before the water is allocated for consumption, including measure of flow and chemistry, measure of requirements of groundwater-dependent organisms and their habitats, by the means of watershed management plans which ensured the protection of GDEs. However, this framework has also faced significant challenges related to implementation and misunderstanding of core principles which has affected the practical implication of the policy intent (Kallis and Butler 2001; Voulvoulis et al. 2017).

13.4.3 Australia

The National Water Commission in Australia is responsible for the management and implementation of the National Water Initiative (NWI) established in 2004 for the protection and allocation of surface and groundwater resources. Efficient allocation of groundwater resources entitlement and the levels of democratic accountability are the major tools that have enabled the policymakers to integrate GDEs in centre of various basin-level developmental plans. The GDE Atlas[4] was created by the National Water Commission (NWC) in Australia for an improved understanding and management of groundwater-dependent ecosystems (GDEs). This Atlas fills a knowledge gap in the form of a countrywide web-based inventory of the GDEs with a large amount of hydro-ecological database present on the Bureau of Meteorology (BOM) server. This proved as an important tool in locating potential GDEs and enabled their regular monitoring and assessment throughout the country (Ross 2016).

13.4.4 Asia

Overexploitation of groundwater resources has become one of the major challenges faced by the Asian countries. Burgeoning population and increasing food demand have led to overextraction of water resources to an extent that the replenishment of the resources has been hampered with few chances of recovery owing to the added impacts of climate change. Research-oriented countries like China and Korea are much more ahead in assessing the upcoming challenges of water scarcity not just for the humans but also its impact on the depending ecosystems (Hu et al. 2018; Xu and Su 2019; Wang et al. 2020a, b), as compared to the other developing Asian countries like India, Bangladesh, Pakistan etc..[5] These South Asian countries with agrarian

[4] http://www.bom.gov.au/water/groundwater/gde/index.shtml

[5] http://en.cgs.gov.cn/achievements/201601/t20160112_35416.html

economies are facing impending water stress and are not yet prepared for the water crisis in the upcoming decades.[6]

13.5 Groundwater Management and GDEs Assessment Concerns

Water bodies ensure nature's contributions through diverse ecosystem functions that ensures human well-being. Diverse rivers, streams, wetlands, springs, estuarine habitats, aquifers etc. located across length and breadth of the country provide varied ecosystem services (Sinclair et al. 2020). In global South, there are different attributes to water scarcity, as well as multiple elements that contribute to the aggravating water shortage that is growing more daunting by the day. Growing urbanization raises concerns about the long-term viability of water resources. During the last two decades, due to a lack of surface water, demand for groundwater resources primarily for drinking and agriculture has risen dramatically in the semi-arid areas in particular and globally in general. Groundwater pollution has ascended intensely in locations where there has been a substantial increase in industrialization and population expansion (Rais and Salam 2020). Urbanization, faster agricultural operations, extensive use of agricultural inputs, and other factors follow. As a result, groundwater pollution, water quality for drinking and irrigation, and geochemical occurrence and distribution have all been extensively studied across the world. Overuse and insufficient replenishment have resulted in a significant drop in groundwater levels over the years (Sishodia et al. 2016). For example, India uses roughly 250 billion m^3 of groundwater each year, accounting for more than a quarter of the world total. The importance of groundwater is demonstrated by the fact that it supplies 60% of irrigated farmland and 85% of drinking water in rural India.[7] As per the Dynamic Groundwater Resources Assessment of India, 2017,[8] the overall stage of groundwater development in the country is 63%. The groundwater extraction levels have exceeded 100% in the states of Delhi, Haryana, Punjab and Rajasthan implying more consumption of groundwater than the annual extractable limits. States and UTs like Himachal Pradesh, Tamil Nadu, Uttar Pradesh, Chandigarh and Puducherry are in the critical stage with groundwater extraction between 70% and 100%. Figure 13.2 shows the graph of states and UTs in India and their stage of groundwater extraction as of 2017.

There have been several policies and laws formed around protection of water resources in India since late 1800s. Some of these were Indian Fisheries Act, 1857; Water Prevention and Control of Pollution Act, 1977 and Coastal Zone Regulation Notification, 1991 are few relevant acts that also address the concerns of water resources protection. National River Conservation Plan (NRCP) and other two

[6] https://apcss.org/Publications/Report_Water&Conflict_99.html

[7] https://www.fao.org/aquastat/en/

[8] http://cgwb.gov.in/GW-Assessment/GWRA-2017-National-Compilation.pdf

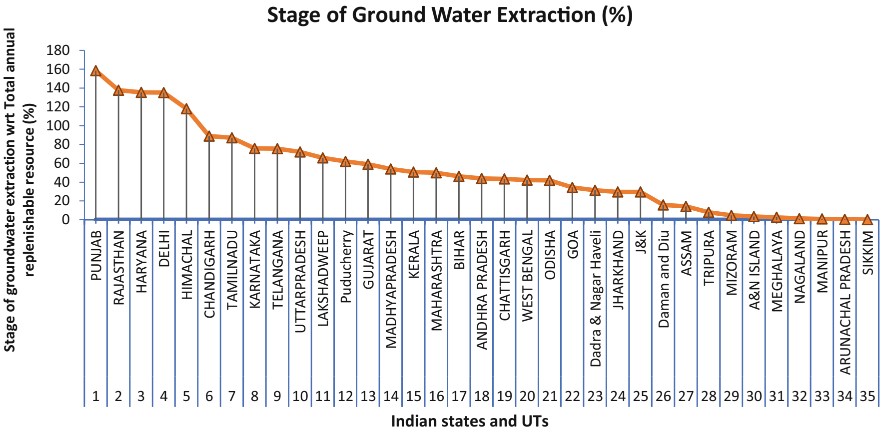

Fig. 13.2 State of groundwater extraction with respect to the annual total replenishable water resources in Indian states and Union territories (derived from http://cgwb.gov.in/Documents/Dynamic-GW-Resources-2011.pdf)

Centrally Sponsored Schemes (CSS) are managed by the National River Conservation Division (NRCD) in MoEFCC. Two centrally sponsored schemes for wetland conservation in the country by MoEFCC are National Wetland Conservation Programme (NWCP) as well as National Lake Conservation Plan (NLCP). The government has launched Ministry of Jal Shakti,[9] Department of Water Resources in 2019, in order to unify all water resources schemes under one umbrella, to address the water shortage, sanitation and quality issues faced throughout the country. The digital Micro-watershed Atlas of India aimed at creation of a web-based monitoring system for transparent regulation and prevention of overlapping of different developmental process, was released on 29th March, 2019 during the Annual Technical Meeting of the Heads of the Offices of Soil and Land Use Survey of India.[10]

Despite these efforts to ensure safe drinking water and sanitation for all, along with the groundwater resources estimation, there is still a larger data gap faced in the form of the assessment of Groundwater-Dependent Vegetation (GDV) and most of the decisions are driven by insufficient and incomplete understanding of this important research context. As discussed above, GDEs are one of the prime consumers of groundwater and have a large number of ecosystem services. The global attention towards GDE assessment, its role in groundwater regulation and the continuous innovations in the methods of GDE estimation, needs to be exercised and implemented to understand the water requirements and consumption by the dependent ecosystems and especially fast-expanding invasive species. Assessment of groundwater-dependent ecosystems or vegetation must be included in policy

[9] https://jalshakti-ddws.gov.in/

[10] https://slusi.dacnet.nic.in/mwanew.html

formation and implementation as the lack of it will lead to unsustainable water laws and increasing groundwater crisis in the country.

13.6 Conclusion

GDEs are existing in nature throughout the period of natural evolution. The ecological, social, cultural, and economic significance of GDEs has only lately been recognised. For many decades, inferential approaches were the primary way of determining the presence/location of GDEs; however, more direct procedures, such as the use of stable isotopes and hourly direct observations of variations in shallow groundwater depth, have recently supplanted them. The most recent advances in GDE assessment are the use of remote sensing tools for identification and estimation of these ecosystems. However, the global interest in GDEs has not yet been picked up by many developed and underdeveloped countries of global South, and the country severely lags behind in its groundwater management approaches with focus only on the population water demand. Thus, there is an urgent need to implement global innovations in groundwater-dependent ecosystems mapping and management in Indian scenario for formation of comprehensive and sustainable groundwater in future.

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Conflict of Interest Authors declare no conflict of interest for this manuscript.

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Advanced Scientific Methods and Tools in Sustainable Forest Management: A Synergetic Perspective

14

Peter A. Khaiter and Marina G. Erechtchoukova

Abstract

The field of forest management is characterized by the presence of diverse stakeholder groups which approach the task from different, sometimes conflicting, perspectives. Owners and timber producers are interested in maximized harvesting of forest raw materials while the goal of a broader public is to conserve forests. Forest ecosystems provide a spectrum of unique goods and services, such as food and medicinal plants, support of biodiversity, water and air quality, wildlife accommodation and climate mitigation. There is an obvious necessity to harmonize the needs of the stakeholder groups whereby forest conservation and logging are complementing, not competing, goals which can be achieved by promoting the ideas of sustainability. The problem of sustainability in forest management is approached from the perspective of advanced scientific methods and tools. A variety of theoretical concepts underlying the idea of sustainability in forestry studies is reviewed, and an integrated framework for a synergetic sustainable forest management is proposed. The framework accommodates various contributing concepts, such as sustainable development and its 17 goals, forest ecological-economic-social systems, forest ecosystem services and benefits, forest informatics, precision forestry, adaptive forest management, and data science. A nine-step roadmap for practical implementation of the framework is suggested comprising of: (1) data acquisition; (2) data storage; (3) data access; (4) data extraction; (5) data preprocessing; (6) data analysis; (7) modelling; (8) optimization; and (9) decision-making. Applications of advanced scientific methods and tools at each step of the roadmap

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are demonstrated. Integration of the multiple technologies and tools is a prominent current trend.

Keywords

Sustainability · Ecosystem services · Machine learning · Decision-making · Vegetation modelling · Agent-based modelling

14.1 Introduction

Forests play a unique role in supporting life on our planet. According to commonly accepted estimates, 1.6 billion people depend directly on forests as a source of their subsistence and 300 million people worldwide live in forests that also shelter "more than three-quarters of the world's terrestrial biodiversity including plants, animals, fungi, and bacteria" (https://www.worldwildlife.org/). Thus, "80 percent of amphibian species, 75 percent of bird species and 68 percent of mammal species" are found in forests (FAO 2020).

In addition, forests fulfil a spectrum of functions that favourably affect human life and the environment. It is enough to mention forest contributes to the provision and support of human health and well-being, biodiversity, ecosystem wellness and stability, quality of air and water, wildlife habitats, recreation and aesthetic enjoyment, etc. Contemporary dispute around climate change led to a deeper realization by the society of a growing role of forests in global nutrient cycling (e.g. Blanco et al. 2005; Kirschbaum 1999; Van der Salm et al. 2006; Zhu et al. 2003) and greenhouse gases sequestration (e.g. Potter et al. 2001; Seely et al. 2002; Uemura et al. 2005; Von Arnold et al. 2005). On the other hand, it has been demonstrated in the studies (e.g. Aber et al. 2001; Dale et al. 2000) that forest ecosystems, in their turn, are affected by extreme weather conditions, and, therefore, a complicated interweaving between natural dynamics, anthropogenic impact, and forest post-impact disturbances cannot be neglected.

According to the report "The State of the World's Forests 2020" of the UN Food and Agriculture Organization, there are ongoing processes of deforestation, fragmentation, and agricultural expansion, and "more than 100 million hectares of forests are adversely affected by forest fires, pests, diseases, invasive species, drought and extreme weather events" (FAO 2020). Though the report noted a positive reduction of the net loss of forest cover from 7.8 million hectares per year in the 1990s to 4.7 million hectares per year during 2010–2020 (FAO 2020), there is still an evident and pressing need for international and national efforts aimed at combating deforestation, and illegal logging and hunting, and fostering sustainability in the forest management practices.

A series of international initiatives has been undertaken over the last years, including the articulation of the Biodiversity Aichi Targets (CBD 2013), 17 Sustainable Development Goals (SDGs) in the 2030 Agenda for Sustainable Development (UNGA 2015), and the current status and trends with regard to biodiversity and ecosystem services in the Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019) promoting solutions that balance the demand for resources supplied by forests with conservation goals. Achieving this harmony requires consolidated efforts at political, administrative and scientific levels to be supported by modern advanced methods and tools.

The purpose of this chapter is to inform readers about advanced scientific methods and information technology (IT) tools applied in modern sustainable forest management. For that purpose, we first review a variety of theoretical concepts underlying the idea of sustainability in forestry studies including the data science field. We argue for an integrated framework of a synergetic sustainable forest management to accommodate various contributing concepts, such as sustainable development (SD) and its 17 goals, forest ecological-economic-social (FEES) systems, forest ecosystem services and benefits (FESB), forest informatics (FI), precision forestry, adaptive forest management (AFM), and data science (DS). We suggest a nine-step roadmap for a practical implementation of the synergetic sustainable forest management theoretical framework and demonstrate how advanced scientific methods and tools are being used at each step of the roadmap.

14.2 Methodology

14.2.1 Scientific Concepts of Sustainability

An internationally accepted definition of sustainable forest management (SFM) describes the notion as "the stewardship and use of forests and forest lands in a way, and at a rate, that maintain their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that do not cause damage to other ecosystems" (www.mcpfe.org). In the broadest sense, SFM means managing forests in accordance with the principles of sustainable development (Kumar and Singh 2020; Kumar et al. 2021a).

The concept of sustainable development (SD) is being promoted since the late 1980s. With regard to environmental issues, *sustainability* can be interpreted as "maintaining natural capital and resources" (Goodland 1995). There are various definitions of sustainable development proposed over the years, of which the most frequently quoted one has been provided in the Brundtland Commission report as "development that meets the needs of present generations without compromising the ability of future [generations] to meet their needs" (Our Common Future 1987). The main idea of the concept is to balance the needs of socio-economic development and the health of the biosphere. There is an opinion (McDonach and Yaneske 2002) that no one knows what this balance is or, indeed, whether the needs of the biosphere have already been compromised. Different interpretations of the notion of sustainability have been offered (Kumar et al. 2019a). Barett and Odum (2000) approached it through the concept of "the optimum carrying capacity".

Thermodynamic laws of energy and entropy have been employed by Jørgensen and Svirezhev (2004) and Norde (1997) and later complemented by the eco-exergy principle (Jørgensen 2006). Valuation of diverse services and benefits generated by the environmental systems has been the cornerstone of the sustainability concept suggested by Khaiter (2005a).

The three dimensions or "pillars" of sustainability, namely, "economic development", "social development" and "environmental protection" have been indicated in the 2005 World Summit on Social Development (UNGA 2005). By analogy from accounting, this expression of sustainability has been named the "Triple Bottom Line (TBL)" approach. In this connection, the US National Research Council noted that the key point in the definition of sustainability is the recognition of the importance of the three pillars (NRC 2011) and their interdependency in a way that the economy can be viewed as a subsystem of the human society, which itself is a subsystem of the global biosphere (Porritt 2006).

It is hard to challenge that the concept of *ecological-economic-social* (EES) systems and ecosystem services they produce (Khaiter 1986, 1990b, 1993a, 1996, 2005a; Gorstko and Khaiter 1991) is a precursor of the TBL notion. An idea to manage the economic and societal development with a view of environmental constraints had been suggested and developed mainly for forested territories since the late 1980s (Khaiter 1989, 1990a, 1991, 1993b, 2005a; Khaiter and Erechtchoukova 2012, 2013, 2017, 2020). The concept of a *forest ecological-economic-social* (FEES) system (Khaiter 1993a) is based on the accounting of the full set of possible forest-related goods and services. The latter can be classified into three main groups: (1) *ecological* benefits, (2) *economic* benefits, and (3) *social* benefits. Table 14.1 is a sample list of forest benefits in each of the three groups.

Table 14.1 Three groups of forest-generated benefits (Khaiter and Erechtchoukova 2010a)

Economic amenities	Ecological amenities	Social amenities
Wood products (timber and fuel wood) Non-timber products: • Wild food (honey, mushrooms, wild fruits and latex, berries, fibres, nuts, hunting meat from wild animals, birds, and fish) • Raw material (cork, resin, mastic gum) • Medicinal plants • Plant genetic resources	Landscape stabilization Soil protection from erosion Soil moisturizing Soil enrichment by nutrients (fertilization) Pest control Water quantity regulation (hydrological function) Water purification (hydrochemical function) Flood control Climate regulation Carbon sequestration Oxygen generation Global warming mitigation Fisheries protection Wildlife habitat	Human habitat function Recreation opportunities Tourist opportunities Aesthetic function Sanitary functions: • Disease buffering • Therapeutic • Dust sequestration • Noise reduction Educational function

Fig. 14.1 17 sustainable development goals (UNDP 2015)

Currently, the importance of ecosystem goods and services for the theoretical and practical sustainability is commonly accepted, notwithstanding the fact that the policy documents do not always explicitly mention them (Geijzendorffer et al. 2017; Griggs et al. 2013; Liu et al. 2015; Wu 2013). The bottom line is absolutely clear: SFM can be achieved only if all the forest-generated goods and services are adequately quantified and incorporated in the decision-making process.

An important milestone in the promoting sustainability has been the 2015 United Nations General Assembly which adopted the 2030 Agenda for Sustainable Development. The document formulated 17 Sustainable Development Goals (SDGs) (Fig. 14.1) and spelled them out in 169 associated targets. The main purpose of the 2030 Agenda has been proclaimed to address "the global challenges we face, including those related to poverty, inequality, climate, environmental degradation, prosperity, and peace and justice" (UNGA 2015). All UN Member States, signatories to the 2030 Agenda, affirmed an imperative that global problems require collective efforts in addressing climate change and preserving the environment.

Two fundamental international policy documents: the 2030 Agenda with its SDGs (UNGA 2015) and the Convention on Biological Diversity (CBD) Aichi Targets (CBD 2013) have been analysed by Geijzendorffer et al. (2017). Both documents have global scope and specify objectives pertaining to sustainable development. The study showed that 12 goals (out of 17 SDGs) and 13 targets (out of 20 Aichi Targets) relate to ecosystem services which proofs the point that sustainable management can be practically implemented only if all the goods and services generated by the affected ecosystems are appropriately incorporated into the decision-making process (Khaiter and Erechtchoukova 2010a).

Larrubia et al. (2017) noted that forests have a crucial role in meeting a number of the SDGs (in particular, SDG 1, SDG 2, SDG 8, SDG 12, SDG 13, SDG 15) given that forest-related services and benefits are multifaceted and wide-ranging, and contributing to basic securities such as food, water, energy and health, thus providing livelihoods for more than a billion people. The later consideration is an evident call for fostering the practices of SFM and a broad application of advanced scientific methods and tools.

14.2.2 Scientific Concepts of Advanced Methods

From historical perspectives, applications of advanced scientific methods in forest research, management, and planning, first of all the use of information technologies and analytical tools, unfolded under two conceptual umbrellas: forest informatics and precision forestry. Forest informatics is a multidisciplinary field of science combining forestry and informatic concepts and theories meant to enrich forest management and forest science (Forest Informatics 2013) by way of integrating "the power of computational and information technologies to organize and analyze biological data from research collections, experiments, remote sensing, modeling, database searches and instrumentation and deliver them to users throughout the world" (Shanmugavel 2008).

Simultaneously, since the early 2000s, a concept of precision forestry has emerged, primarily in North America and Europe (Fardusi et al. 2017). Originally, the term was introduced in 2001 at the First International Symposium on Precision Forestry (Becker 2001). Dash et al. (2016) note that a multitude of definitions and applications of the term appeared since then. In essence, a synthetic definition of the notion views precision forestry as "the use of information technologies and high technology sensing and analytical tools to support site-specific, economic, environmental, and sustainable decision-making for the forest sector supporting the forestry value chain from bare land to the customer buying a sheet of paper or board" (Becker 2001; Taylor et al. 2002; Ziesak 2006; Kovácsová and Antalová 2010).

In addition, Tuček (2013) following and extending ideas of Heinimann (2010) argued in favour of combining the concepts of adaptive forest management and precision forestry on the basis of geographic information and geoinformation technology which he considers as the key tools for precision forestry. Given the importance of the data aspect in the whole sequence from data collection, storage, retrieval, and subsequent processing and transformation into information and knowledge by means of mining, analysis, modelling, and decision-making for practical forest management, we suggest to include data science as a necessary methodological component of the SFM. Data science is a cross-disciplinary field of studies which develops and applies "scientific methods, algorithms and techniques to primarily extract knowledge and useful relevant insights based on a given dataset" (Dhar 2013). In this way, data science field aggregates vast variety of statistical, data analytical as well as informatics tools to analyse, understand, and derive insights and conclusions (Hey 2009). Therefore, data science employs a wide skill set spanning from graphics design and data visualization, statistics, information science and integration to complex computer systems and telecommunication technologies to support business analysis (Loukides 2020). A life cycle of a data science project includes phases of data collection and extraction, preprocessing to prepare for analysis, data exploration and variable selection, model planning and building, and communication of the results to inform the stakeholders (Cady 2017; Data Science 2015).

In our opinion, each of the concepts briefly reviewed above is important for the promotion of the idea of sustainability in forest management. We argue for a synergetic sustainable forest management (SSFM) theoretical framework on the basis of the following contributing concepts: (a) sustainable development (SD) and 17 SDGs; (b) forest ecological-economic-social (FEES) systems; (c) forest ecosystem services and benefits (FESB); (d) forest informatics (FI); (e) precision forestry (PF); (f) adaptive forest management (AFM); and (g) data science (DS) as shown in Fig. 14.2.

14.3 SSFM Roadmap

By its nature, the process of decision-making is highly information-dependent whereby multiple transformations and processing of information are taking place. To that same extent, comprehensive information is necessary for promoting sustainability in the forest resource management practices (Holopainen et al. 2014). Ross (2015) conducted a review of the indicators to measure sustainability in forestry and classified them in three groups: (1) indicators specific to forests; (2) indicators encompassing the entire agricultural sector, of which forestry is a sub-sector; and (3) indicators pertaining to other related sectors affecting forestry (Table 14.2). Even more detailed set of indicators and criteria for the forest domain is provided by Linser et al. (2018).

It is evident how crucially important each stage is from the primary data collection through to the final decision release. In addressing said challenge and for practical implementation of the SSFM theoretical framework, a nine-step roadmap is suggested comprising of: (1) data acquisition; (2) data storage; (3) data access; (4) data extraction; (5) data preprocessing; (6) data analysis; (7) modelling; (8) optimization; and (9) decision-making (Fig.14.3). In the subsequent sections, we review application of advanced scientific methods and tools at each stage of the framework.

14.3.1 Data Acquisition

Multifaceted nature of forest management activities requires to collect a large amount of data. In the past, the main (if not even the only available) source of data had been in situ monitoring of the forest stand. Common attributes measured in situ are species, tree status, and diameter at breast height (dbh) though timber quality and tree height can be simultaneously taken (Liang and Gamarra 2020). Basal area,

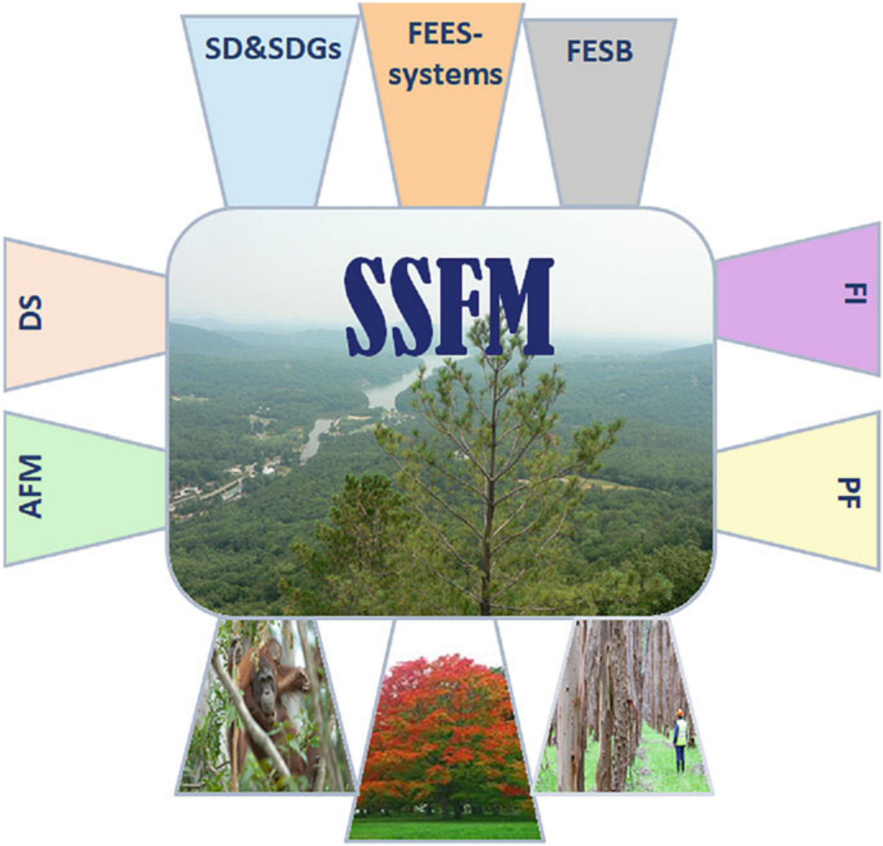


Fig. 14.2 Theoretical framework of the synergetic sustainable forest management (SSFM). *SD* sustainable development, *SDGs* Sustainable development goals, *FEES* forest ecological-economic-social systems, *FESB* forest ecosystem services and benefits, *FI* forest informatics, *PF* precision forestry, *AFM* adaptive forest management, *DS* data science

species diversity, site index, stand volume, and other metrics can be obtained through derived computations (Liang and Gamarra 2020).

With the development of modern technologies, it has been extended by various geospatial means which include Geographical Information Systems (GISs), Remote Sensing (RS) and Global Positioning Systems (GPS) offering compelling techniques of mapping, monitoring, surveying, classification, characterization and change detection of natural resources (Kumar et al. 2019b, 2021b; Kala and Kumar 2022; Pokhriyal et al. 2020). Applications of geospatial techniques for forest management are reviewed by Fardusi et al. (2017), Kala and Kumar (2022) and Tuček (2013).

Limitations of in situ observations in that they are often sparse and localized can be complemented and overcome by the advantages of remote sensing (Buhne and Pettorelli 2018; Olokeogun and Kumar 2020; Reddy 2021; Singh et al. 2020b, c).

Table 14.2 Performance indicators for SFM (adopted from Ross 2015)

Forest-specific indicators	Agriculture sector-wide indicators	Indicators of other related sectors
Forest cover	Land tenure	Socioeconomic status
Deforestation rate	Land use	Environment
Protected areas	Land cover	Disaster risk management
Area of forest under management or designated for specific uses	Biodiversity and conservation of fragile or high-value ecosystems	Carbon and energy productivity
Climate change mitigation and adaptation		Use of renewable energy and fossil fuels
Forest governance indicators		Policy and governance
Trade data		
Business statistics pertaining to forest products		Private sector and public-private partnerships
Forest policy frameworks		
Public financial management in forest sector		

Fig. 14.3 Roadmap of the synergetic sustainable forest management (SSFM)

Talbot et al. (2017) define remote sensing as “the acquisition of information about an object without making physical contact with it” and by means of sensors installed on various platforms (or carriers), such as satellite, aeroplane, unmanned aerial vehicle (UAV) or a ground-based vehicle or human. In application to forest data collection, Liang et al. (2015) list laser scanner platforms for Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS), Airborne Laser Scanning (ALS), and Personal Laser Scanning (PLS). In relation to forest inventory, Bauwens et al. (2016) additionally introduced the concept of Hand-Held Mobile Laser Scanning (HMLS). Fardusi et al.

(2017) indicated a growing number of remote sensing applications in forestry over the last few decades which they attributed to the increased availability of ALS devices, particularly Light Detection and Ranging (LiDAR) sensors.

Forest variables are measured at different spatial resolutions ranging from millimetres to kilometers and global scales as well as temporal scales where phenomena of interest can last from short time periods to much longer-period occurrences (Fardusi et al. 2017). A correspondence between remote sensor deployment platforms and their spatial coverage and temporal resolution is given by Talbot et al. (2017).

Reddy (2021) analysed the role of remote sensing in data supply of biodiversity studies based on 2682 publications over a ten-year period 2011–2020. The following applications of remote sensing from the study are relevant to forest management: vegetation type, forest cover, ecosystems/communities/species, vegetation-climate interaction; phenology monitoring, biomass, carbon pools and fluxes, disturbance regime, and trees outside forest (Kumar et al. 2021c).

These methods of direct or targeted data acquisition are being complemented nowadays by indirect Big Data sources whereby many data originally not captured specifically for environmental purposes may be successfully used in the domain (Vitolo et al. 2015). According to Ghani et al. (2014), Big Data is the "ultra large bodies of data that have not been prospectively limited in size or scope by the intent to address specific research questions or disease conditions, and that grow continuously and rapidly". Granell et al. (2016) summarized a number of Big Data characteristics as being huge in volume, created in near real time (with data streams continuously generated and collected), diverse in variety (structured and unstructured in nature), and exhaustive in scope (capturing entire populations or, at least, larger datasets). The classification of Big Data is based on five aspects: (1) data sources, (2) content format, (3) data stores, (4) data staging, and (5) data processing (Hashem et al. 2015). The data sources dimension includes: (a) social media (i.e. data generated from a wide number of Internet applications and websites, such as Google, LinkedIn, Twitter, Facebook); (b) machine-generated data (i.e. information automatically generated from a hardware or software without human intervention, such as web server or network event logs); (c) sensing (i.e. information derived from devices that measure physical quantities and transform them into signals, such as thermostat, barometer, CO_2 measurement instruments); (d) transactions (i.e. information that involves a time dimension to describe the data, such as workflow or logistics data; (e) IoT (i.e. data generated by large number of devices connected to the Internet, such as smartphones, digital cameras and tablets) (Calza et al. 2020; Hashem et al. 2015). Examples of indirectly obtained environmental data include geotagged photographs with information about land or forest cover and meteorological conditions, forest disturbance patterns, online social network interactions and so forth (Vitolo et al. 2015).

14.3.2 Data Storage

Selection of a software for managing environmental data is largely predetermined by the types of data collected. Given that forest monitoring systems generate mainly quantitative data, relational databases remain the predominant choice in storing and sharing environmental data (Vitolo et al. 2015). As of October 2021, the top five most widely used relational database management systems (RDBMS) have been: Oracle, MySQL, Microsoft SQL Server, PostgreSQL, and IBM Db2 (https://db-engines.com/en/ranking). These software tools provide excellent support for storage and manipulation of numerical data. In view of an increasing trend in applying images and georeferenced data in forest management, pure relational systems have been extended by object-relational data structures on the basis of the SQL 1999 standard. Evolving RDBMSs are now able to support heterogenous data structures and new data types coupled with excellent search capabilities and operations in multi-user environment.

However, RDMSs are lacking the possibility of interactive examination of data as well as comprehensive analysis of large quantities of data (Tuček 2013). To address these deficiencies, data warehouses can be used instead (Erechtchoukova and Khaiter 2004). Data warehouses implement multidimensional data model by integrating data from multiple databases and are more analytically oriented, without frequent transactional updates (Tuček 2013). Most data warehouses are used for interactive data analysis through OLAP (Online Analytical Processing) systems, reporting services, statistical analysis, and data mining techniques (Shekhar et al. 2009).

NoSQL databases are generally a better choice for storing unstructured data. They are meant to overcome the inflexibility of relational databases in processing the highly heterogeneous data, and to support distributed queries (Xiang and Hou 2010). NoSQL databases do not have a predefined schema but, instead, store data in more flexible internal structures, commonly hierarchical "key–value" pair arrays (e.g. Amazon DynamoDB). Collections of relatively long text documents are better supported by Document DBMSs, such as MongoDB or Apache CouchDB. Even though storing textual data in a database extends the available data, it requires specific approaches to data processing including text mining techniques.

Sensor-generated data come in large volumes with the high speed and require new approaches to data storage and processing. When incorporated with the result of observations obtained traditionally, the sensor data may uncover interesting phenomena. However, to support such analysis, new approaches to data analysis are required. Big Data analytics develop advanced techniques for storage and processing of very large diverse datasets. Utilization of software tools, such as Apache Hadoop for distributed data processing and its integration with machine learning engines like Apache Spark, can bring the decision support at the new level (https://www.ibm.com/analytics/hadoop/big-data-analytics).

Spatial-temporal dimensions of forest management data make geographic information systems (GISs) an attractive storage option. It has been observed that the use of GISs in forestry is expanding over the last decades, and the systems are widely applied, both for practical and academic purposes (Li et al. 2007; Grigolato et al. 2017). It should be noted that the functionality of GISs goes far beyond pure data storage, and these information systems are also meant to capture, manage, manipulate, analyse, and visualize all types of geographical data.

There is an obvious recent general trend toward cloud computing whereby the delivery of computing power and storage capacity occurs in the form of on-demand services over the Internet, without direct active management by the end recipients. Three types of services comprise cloud computing: (1) infrastructure as a service (IaaS); (2) platform-as-a-service (PaaS); and (3) software-as-a-service (SaaS). Cloud computing has unavoidably affected approaches to data management. Major DBMS vendors offer cloud-based versions of their products while simultaneously withdrawing the support of the traditional formats, thus forcing environmental organizations to store their data on the cloud. This trend has also shifted the attention of researchers and practitioners from pure technical issues of hardware configuration, network connectivity and scalability, database backup and recovery towards integration of heterogenous data from various sources and their processing in support of decision-making at the local and global levels.

Nowadays, the cloud computing technology integrates the GIS applications (Savvaidis and Stergioudis 2012), for example, under the SaaS model whereby users may rent application software and databases while cloud providers manage the infrastructure and platforms on which the applications run. Stergioudis (2016) reports on the application of Web GIS for forest management in Greece as a common tool for many stakeholders enhancing cross-agency cooperation, minimizing data redundancy and providing a common framework for analysing forest data.

14.3.3 Data Access

Robinson and Hamann (2011) noted that “little systematic attention has yet been paid to the tools and protocols that are necessary to provide robust and convenient access to data”. Liang and Gamarra (2020) indicate the critical importance of an open access to global forest data, especially in situ records, for saving the world’s forest systems, particularly for the monitoring and mitigation of forest degradation, deforestation, biodiversity loss, and climate change.

Over the past years, national and international agencies and organizations undertook a lot of efforts to make forest-related data accessible to various categories of users. Thus, the FAO has launched an open data initiative targeting to increase transparency in forestry (CBIT-Forest, http://www.fao.org/in-action/boosting-transparency-forest-data/en/) (Fig. 14.4). Another example of this kind is an online platform of the Global Forest Watch (GFW) which allows anyone to access near real-time information on forest dynamics in terms of tree cover, gain and annual loss, CO2 emissions, and biomass loss (https://globalforestwatch.org).

A number of online databases are supported by the European Forest Institute (EFI): a forest inventory database (EFISCEN), a long-term forest resources assessment database (LTFRA), a forest products trade flow database (FPTF), and a

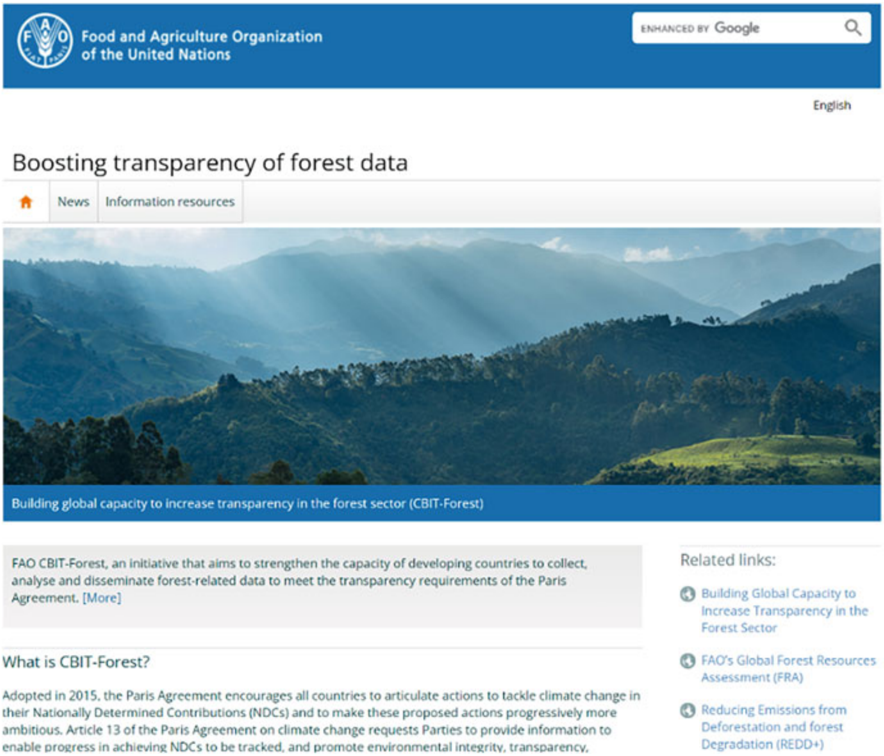


Fig. 14.4 Home page of the FAO-CBIT Forest program

database on forest disturbances in Europe (DFDE) (https://efi.int/knowledge/databases). EFISCEN database contains forest inventory data for 32 European countries derived from their national forest inventories and is freely accessible to all registered users.

The US Forest Service Agency offers an open-access Geospatial Data Discovery Tool to access data about individual forests or grasslands or about an area of interest. Users can find and download datasets by topic area or theme (e.g. forest management, ecosystems, vegetation, recreation, fire and aviation) or find and use map services published by the Agency (https://data-usfs.hub.arcgis.com/).

The UK Forest Research Agency provides an Open Data Site for spatial data that can be used in Geographic Information Systems (GIS) (www.forestresearch.gov.uk/). Spreadsheets include statistics for England, Scotland, Wales, and all of the UK on such measures as woodland area and planting, timber trade, climate change, environment, recreation, employment and businesses, finance and prices and so on.

14.3.4 Data Extraction

Data extraction is the process of retrieving data from a storage source system. In conventional DBMSs, data selection is done by a request written in a database language, such as Structured Query Language (SQL), formulated by the user or application. The emergence of cloud storage and cloud computing caused a major impact on the entire data management, particularly enabling companies and organizations around the globe to access data in real-time regime, without having to maintain their own servers or data infrastructure (www.talend.com) by utilizing specially designed extraction tools with user-friendly interfaces.

Zhao et al. (2020) processed Light Detection and Ranging (LiDAR) point cloud data to extract accurate forest stand parameters of the mean height (H), average diameter at breast height (D), basal area (G), and stand volume (V). At the same time, Dash et al. (2016) noted a specific challenge forestry researchers are facing in the development of methods to extract information relevant for forest management from growing mass of data.

14.3.5 Data Preprocessing

The notion of data preprocessing is mostly used within the context of data science and machine learning studies to deal with the issues of incomplete, inconsistent, lacking and/or erroneous data. However, it is likewise important for the domain of forest sustainability, especially in view of a broad application of advanced scientific methods and tools whereby research datasets are aggregated from different data sources and presented in different data formats. In general, it means the methods of turning the raw data into a format suitable for the subsequent analysis and modelling steps. Data preprocessing tends to be the most labour-intensive step taking at least 50% of the project time (Data Science 2015), but remains largely underestimated in the forest-related studies.

14.3.6 Data Analysis

Once the datasets are preprocessed, they can be analysed aiming at getting maximum insights of and examining the data as a preliminary step before building a model. Data visualization, univariate and multivariate statistical analyses are the most popular techniques applied in this step.

14.3.7 AI/ML Techniques

Artificial Intelligence (AI) is an interdisciplinary "field concerned with building smart machines capable of performing tasks that typically require human intelligence" (https://builtin.com/) and focusing on automation of intelligent behaviour, that is, an ability to perceive, analyse and react (Chowdhary 2020).

Machine Learning (ML) is a branch of AI applied in data-rich problems to discover new knowledge by generalizing from examples (Nwanganga and Chapple 2020). ML techniques are structured in a way to enable systems to learn and make predictions based on historical data. ML techniques largely belong to one of the two types: (1) supervised learning algorithms that operate on labelled examples from the past data, and (2) unsupervised learning algorithms that find hidden patterns in input data without prior labelling (Bell 2020; Nwanganga and Chapple 2020).

Recent developments in the field of AI have brought revolutionizing changes and made AI applications an integral part of almost every branch of human activities. While the field of AI embraces a broad range of ideas and techniques, the most prominent applications are related to ML algorithms which is determined by the presence of volumes of data, not available ever before. Not surprisingly that AI/ML techniques are being nowadays widely employed to solve various tasks of forest management, such as risk and hazard assessment, vulnerability mapping, forest type detection, disease and pest outbreak control, biomass and carbon stock assessment, biodiversity characterisation, site suitability study, phenological study, forest fire early warning, etc. (Crisci et al. 2012; Joshi et al. 2021; Kumar 2021).

Wang et al. (2021) examined the main applications of deep learning (DL) methods in forestry and found their wide use for the surface quality evaluation of sawn timber, remote sensing image recognition for monitoring and analysis of plant growth status, prediction of wood moisture content and classification of forestry information texts. Forest vertical structure is a key cursor of forest vital conditions, however, being often constrained in forest surveys due to the reasons of time and budget intensity. Kwon et al. (2019) suggested Support Vector Machine (SVM) ML technique to label the vertical structure of forests on the basis of remote sensing RGB aerial photographs. MacMichael and Si (2018) reported on the use of ML to predict tree cover types to address challenges experienced by the US forest management agencies. Ahmadi et al. (2020) demonstrated the advantage of ML models in predicting the forest stand characteristics in temperate forests, namely, the basal area, stem volume and density. Lee et al. (2018) applied ML approach to operationally updated stand-level forest inventories with highly mixed tree species.

Vega Isuhuaylas et al. (2018) investigated three supervised ML algorithms: Support Vector Machine (SVM), Random Forest (RF), and k-Nearest Neighbour (kNN) – for mapping the natural forests in the Andes (Peru) under the conditions of complex topography and mixed fractional land cover. A better classification accuracy of SVM and RF methods was demonstrated in the study, particularly in separating forest cover from shrubland which is important for planning and supporting the conservation activities in the region. Deep learning ML algorithms have been applied for satellite imagery processing for deforestation detection and improved forestry monitoring in Guatemala (Wyniawskyj et al. 2019).

Šerić et al. (2018) presented an AI/ML framework of intelligent forest fire monitoring and surveillance system deployed in coastal part of Croatia. Qu and Cui (2020) demonstrated the ability of an automatic ML framework combined with regional meteorological data and forest fire characteristics to improve the accuracy of forest fire predictions and serve a basis for decision-making in forest risk management.

Moore and Lin (2019) applied two ML algorithms, namely, Random Forest and Gradient Boosting Trees, to a long-term dataset of 157,000 observations on tree growth of radiata pine (*Pinus radiata* D. Don) in New Zealand to determine the drivers of attrition losses from wind. Also, for improved wind-damage prediction, Hart et al. (2017) used RF classifier as a feature-selection technique on data collected in two forests within South-West France to determine a limited set of relevant variables most suitable for developing risk assessment methods and suggesting forest management strategies on future damage reduction.

14.3.7.1 ML Tools and Languages

Data analysis and ML applications require specialized programming languages and software tools. The most popular languages for the purpose are Python and R. Both of them are open-source programming languages offering variety of ML packages and visualization tools. A free download of Python is available from www.python.org website (Fig. 14.5), and R free download can be found on R Project website at www.r-project.org (Fig. 14.6). Many free and open-source ML tools are available (Table 14.3).

14.3.8 Modelling

Modelling in forest management is a long-standing discipline. Hoganson and Burk (1997) traced it back to the 1849 Faustmann formula. A variety of models has been developed in the course of subsequent 170+ years (Kumar et al. 2018; Kumar et al. 2019c; Kumar et al. 2020a, b; Rawat et al. 2020), ranging in terms of their temporal resolution (daily versus annual versus decadal), reliance on data (empirical versus

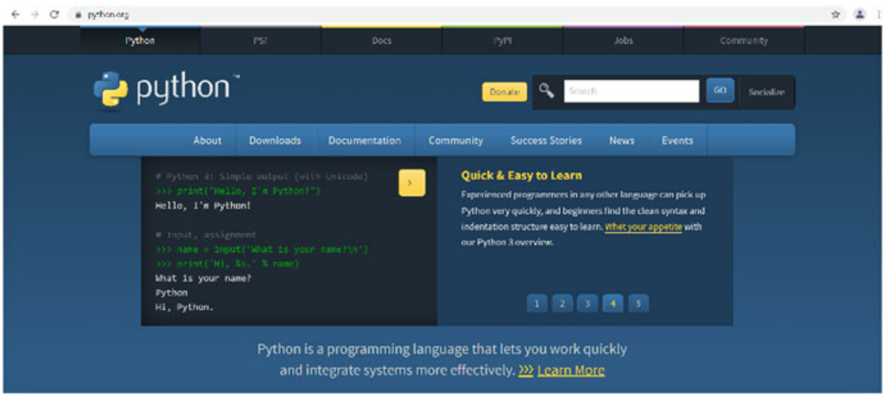


Fig. 14.5 Home page of www.python.org

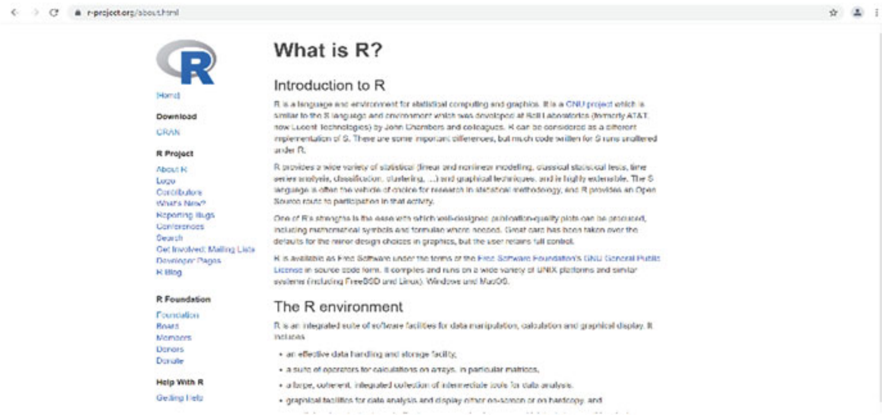


Fig. 14.6 "About R" page of www.r-project.org

Table 14.3 Machine learning (ML) software tools

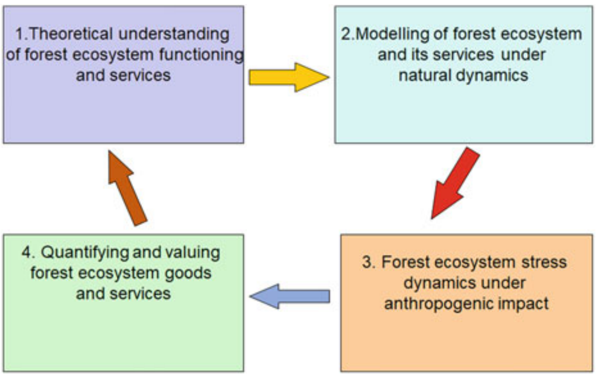
Tool	Operating system	Cost	Language	Algorithms
KNIME	Linux, OS X, Windows	Free and opensource	Java	Guided Analytics Enterprise Reporting Business Intelligence Data Mining Deep Learning Data Analysis Text Mining Big Data
Weka	Linux, OS X, Windows	Free and open source	Java	Data preprocessing Clustering Classification Regression Visualization Feature selection
Orange	Linux, OS X, Windows	Free and open source	Python, Cython, C++, C	Data visualization Machine Learning Data mining Data Analysis
Scikit Learn	Linux, OS X, Windows	Free and open source	Python, Cython, C, C++	Data preprocessing Classification Regression Clustering
Keras.io	Cross-platform	Free, open source	Python	Neural networks
Shogun	Cross-platform	Free, open source	C++	Regression Classification Clustering Support vector machines
Accor. Net	Cross-platform	Free, open source	C#	Classification Regression Clustering
Caffe	Linux, macOS Windows	Free, open source	C++	Deep learning
PyTorch	Linux, macOS Windows	Free, open source	Python C++ CUDA	Deep learning

mechanistic), spatial scale (stand versus individual tree), representation of competitive processes (distance-independent versus distance-dependent), and degree of stochasticity (Twery and Weiskittel 2013; Kalra and Kumar 2018). Fontes et al. (2010) classified models used in forest management into three large groups: (1) empirical models (EMs) using statistical dependencies of target variables, such as timber production, on a number of predictor variables available either from forest inventories and site data; (2) process-based models (PBMs) which explicitly consider physiological processes in forest dynamics, such as photosynthesis, transpiration and respiration along with environmental factors influencing those processes; and (3) hybrid models (HMs) combining the features of EMs and PBMs. Twery (2004) analysed the following categories in forest management modelling: growth and yield models, regeneration models, mortality models, habitat models, harvest-scheduling models, and recreation-opportunity models.

An agent-based approach has brought a new paradigm in modelling of human activities. As summarized by Bonabeau (2002), "in agent-based models (ABMs), a system is modeled as a collection of autonomous decision-making entities called agents" and the relationships between them. Each agent assesses its situation individually and decides on the behaviour based on a set of rules. As a result, an ABM can generate useful information about the dynamics of the underlying real-world system. The integration of ABMs with other modelling techniques may be very fruitful. Spies et al. (2017) examined alternative management scenarios in a fire-prone landscape in Oregon, USA, by applying a human and natural systems framework coupled with an ABM to understand the effect on fire and ecosystem services, and to facilitate public discussions and development of policies and practices. Other ABM applications have been reported by Campo et al. (2009), Purnomo and Guizol (2006), Sotnik et al. (2021), Wimolsakcharoen et al. (2021), and Zupko and Rouleau (2019).

Implementation of the proposed SSFM framework requires to quantify the forest ecosystem services and benefits. Mostly, these quantitative measures require models of the corresponding phenomena (Khaiter 1990a, 1993a, 2005b). To address this issue, the four key elements are to be elaborated as shown in Fig. 14.7. Details on

Fig. 14.7 Modelling elements of SSFM framework



each key element can be found in our prior publications (Khaiter and Erechtchoukova 2009, 2010a, 2010b, 2012, 2013, 2014, 2017, 2019).

Complex process-based or data-driven models are required to support these elements of the framework. For example, a simulation model "Forest hydrology" (SMFH) has been developed (Khaiter 1993a) to quantify the hydrological function (i.e. water regulating service) of a forest ecosystem and its variation in the scenarios of anthropogenic impact.

14.3.9 Optimization

An optimization problem is concerned with seeking to minimize or maximize a goal function satisfying certain constraints. Diverse optimization techniques have been applied in forest planning and management to solve various practical problems since the early 1960s (Rönnqvist 2003; Kaya et al. 2016), or even earlier, from the late 1950s (Bare et al. 1984). One of the common objectives in forestry is to determine long-term timber harvest schedules maximizing harvested volume (or the net profit) under various constraints (Liu et al. 2006). Such constraints may limit the minimum harvest age, allowable opening size, or budget to control the dynamic growth of the forest resources over the multiple time periods as well as environmental or sustainability considerations. Table 14.4 provides sample optimization projects on long-term harvest scheduling.

Recent scientific developments have made it possible to combine optimization models with AI/ML methods. Thus, heuristic techniques, such as genetic algorithms, local search, simulated annealing, multi-start methods, taboo search, have been applied to solve complex problems of forest management (Martin and Otto 1996; López et al. 2014; Serrano-Ramírez et al. 2021).

14.3.10 Decision-Making and Decision Support

Broadly, decision-making is a process of selecting the best solution from a set of possible alternative options. It assumes that objectives of decision-making are established, and the alternative actions can be evaluated against the objectives to choose the one that is either optimal or at least satisfactory, as articulated by Simon (1955). A comparison study of optimal versus satisfactory decision-making by Krawczyk et al. (2012) demonstrated that the latter approach is able to generate more practical strategies in the cases where multiple objectives are to be achieved. It should, however, be noted that this outcome is not universal and will vary depending on the specific features of the problem at hand.

A decision-support system (DSS) is a computerized information system aimed to support and improve the effectiveness of decision-making activities by way of integrating decision-making framework with computer-based information systems (Liu et al. 2010). Over time, the field of decision-making and DSS has expanded by integrating such disciplines as organizational studies, AI, operations research, and

Table 14.4 Sample optimization projects on long-term harvest scheduling

Optimization technique	Description	Author(s)
Multi-objective optimization	Model is based on functional zoning, i.e. dividing a forest under management into three zones: (a) conservation, (b) wood extensive production, and (c) wood intensive production; solved through six heuristic techniques: Local search, local beam search, multi-start, and three hybrids composed by simulated annealing with each of the heuristic techniques	Serrano-Ramírez et al. (2021)
Mixed-integer linear programming	Model deals with the minimum patch size problem in forest harvest scheduling and aims to mitigate the negative impact on wildlife habitats; solved using the branch and bound algorithm	Rebain and McDill (2003)
Dynamic programming	Models address adjacency in large harvest scheduling problems to balance management activities such that adjacency constraints are satisfied and net returns are maximized; either forward or backward recursion; overlapping subproblems solved sequentially in a moving-windows fashion	Hoganson and Borges (1998)
Simulation combined with dynamic programming	Model generates long-term harvest schedules that maximise net profit on the basis of the most complete set of ecosystem services; solved using backward recursion	Khaiter (1996)
Multi-objective optimization combined with simulation modelling	Model finds an optimum desired percentage of the forest area maximizing non-timber goods and services and minimizing maintenance- and protection-related expenses, both parts computed by a simulation model; solved using Pareto efficiency	Khaiter (2005a)

management information systems (Vásquez et al. 2021). These features are complemented by such activities as information acquisition pertaining to the problem, data analysis to develop intelligent recommendations, specification of the suitable actions to achieve the objectives and solve problems as well as forming the record of acquisition, analysis, and application of information (Zimmerman 2012). In the last decades, a number of DSSs have been built for various purposes of forest management (Reynolds et al. 2008). These systems target such areas as multi-criteria decision-making (MCDM), spatial forest planning, group decision-making, pest control and forest damage due to wind or wildfire, and financial decision-making under uncertainty (Segura et al. 2014). There are DSSs aiming to project the future climates and to evaluate the impacts of climate change on forestry (Czimbera and Gálos 2016; Kumar et al. 2020a).

Scope-wise, DSSs can be designed to address one particular problem or to solve complex issues of forest management. Thus, Vásquez et al. (2021) reviewed

183 studies on different types of DSSs in the domain of wild land fire management to solve the tasks of prevention, prediction, monitoring, detection, and simulation. At the same time, forest management is a multifaceted matter that should take into the account many economic, social, legal, administrative, and environmental aspects. However, according to Segura et al. (2014), DSSs are less concerned with social and environmental objectives while focusing mainly on economic and technical considerations. As a positive trend, we can note that sustainability of ecosystem services (ES) and multi-purpose forest management are increasingly becoming the subject of forest planning (Kumar et al. 2020b; Kumar and Singh 2020; Raum 2017).

A transition of forest management from primary focusing on harvesting timber towards broader ideas of sustainability requires adequate methodology and theoretical frameworks. DSS "Forest Management" is an early sample development implementing the concept of the forest EES-systems, goods and services they produce and their monetization to determine the best management practices in forest exploitation (Khaiter 1993a). Sacchelli (2018) offers a more recent development of this approach. Nowadays, a solid theoretical basis is getting an instrumental support from modern scientific tools offered by Data Science, Artificial Intelligence and Information Technologies, first of all, on the part of GISs, IoT and Satellite Remote Sensing (Singh et al. 2020a).

Marano et al. (2019) noted that the DSSs integration with GIS tools resulted in the appearance of the spatial DSSs (S-DSSs) which are more effective in analysing complex spatial problems and solving multipurpose problems of forest resource management. Recent applications of web technologies are also important for promoting participatory decision-making. Open-access features of the systems enable a broader public involvement in decisions design by virtue of a better understanding of environmental issues, developing and evaluating the alternatives, and projecting the consequences of intended actions (Vacik and Lexer 2014).

Successful utilization of advanced information technologies to support decisions in forest management has been reported in the scientific literature. According to Vásquez et al. (2021), state-of-the-art solutions in DSSs for wildland fire management combine various modern technologies, such as Remote Sensing, AI, Big Data, 3D image and photo processing, as well as Cloud Computing and data from social networks. Forest fire detection systems on the basis of IoT are reported by Pavitra et al. (2020), Scicluna (2020), and Srividhya and Sankaranarayanan (2020) while de Almeida et al. (2020) and Moussati et al. (2020) demonstrate the ability of Deep Learning-based tools to cope with this problem. Wildfire prevention and management using Big Data analysis is shown in papers of Athanasis et al. (2017, 2019) and Lin et al. (2018). Data mining techniques (Saoudi et al. 2016; Aakash et al. 2018) and ML methods (Sayad et al. 2019; Tien Bui et al. 2019) are used for forest fire analysis and prediction. There are systems utilising machine vision for monitoring (Liu et al. 2011) and warning (Peng et al. 2020) in the cases of forest fires. Satellite data are applied for fire risk assessment (Chen et al. 2015; Jang et al. 2019). It is reasonable to expect a further development of the new generations of DSSs integrating multiple modern technologies and tools.

14.4 Conclusions

Various stakeholders in forest management approach the task from different, sometimes conflicting, perspectives. Owners and timber producers are interested in maximized harvesting of forest raw materials. The aim of a broader society is to conserve forests. Forest ecosystems provide food and medicinal plants, support biodiversity, water and air quality, provide wildlife habitats and mitigate climate. There is an obvious necessity to harmonize the needs of the stakeholder groups whereby forest conservation and logging are complementing, not competing, goals which can be achieved by promoting the ideas of sustainability.

In this chapter, theoretical concepts underlying the idea of sustainability in forestry studies are reviewed and an integrated framework for a synergetic sustainable forest management is proposed. The framework accommodates such contributing concepts as:

- Sustainable development and its 17 goals.
- Forest ecological-economic-social systems.
- Forest ecosystem services and benefits.
- Forest informatics.
- Precision forestry.
- Adaptive forest management.
- Data science.

A nine-step roadmap for practical implementation of the framework is also suggested. The role of advanced scientific methods and tools at each step of the roadmap is analysed. It can be seen from the conducted study that state-of-the-art solutions offer novel sources of data generated by Remote Sensing, Internet of Things, and social networks as well as compelling techniques for mapping, monitoring, surveying, classification, characterization and change detection in forest ecosystems.

Recent data science methods allow to systematically preprocess and analyse volumes of acquired data and transform them into information and knowledge. Modelling methods are able to capture a complex behaviour of forest ecosystems and predict their natural and anthropogenic dynamics. The tools of decision-support incorporate achievements of various disciplines, including AI, optimization, management information systems, and organizational studies targeting the development of intelligent recommendations and generation of scientifically sound solutions for the needs of forest sustainability.

Web technologies and open-access features of the information systems enable an informed participation of a broader public in the decision-making process by virtue of a better understanding of environmental issues, developing and evaluating the alternatives, and predicting the possible results of intended actions. A current trend on integrating the multiple advanced technologies and tools in modern information systems used in the SSFM domain is clearly noticeable and demonstrated on a number of examples. It is reasonable to expect that this tendency will go on and even gain further momentum in the future.

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15 Application of Dynamic Vegetation Models for Climate Change Impact Studies

Keshav Tyagi, Manoj Kumar, and Martin Drews

Abstract

The Earth's climate and its interactions with vegetation have become a major focus of contemporary climate change research. Hence, climate change is associated with widespread implications for the structure and function of vegetation all over the world. In particular, for terrestrial ecosystems where changes are likely to become increasingly prominent in the coming decade, to advise important societal decisions, understanding ecosystem behavior to changing climate is crucial. For this aim, integrated model-based approaches have been widely adopted. For example, the development of models for simulating the response of vegetation to climate and other associated growth variables have recently highlighted key processes that control the composition and functioning of forest ecosystems. Dynamic vegetation models simulate the spatially explicit response of land surface and terrestrial vegetation processes to climate change across the time slices ranging from seconds to multi-decades. Employing different process configurations and assumptions, different dynamic vegetation models can also be used to probe the inherent uncertainty related to our current scientific understanding of vegetation processes and their model formulation. Uncertainty in understanding impacts using these models is often introduced by the climate forcing, adding elements of scenario, the inherent uncertainty of model, and natural variabilities. For this reason, validation of dynamic vegetation models against

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ground observations is essential for ensuring confidence in the results of climate change impact studies. In the following, we present a coherent view on how to apply dynamic vegetation models for assessing the climate change impact on forests.

Keywords

Physiological processes · Biosphere · Forest ecosystem · Global change · Productivity

15.1 Introduction

Terrestrial vegetation plays an active role in shaping the Earth's environment (Foley et al. 1996). Vegetation influences the global and local climates in many different ways, including through the carbon and hydrological cycles, and is itself influenced by climate change, including increasing temperatures and changing precipitation patterns. In recent years, researchers have been concentrating their efforts on understanding the impact of climate change on vegetation dynamics (Cramer et al. 2001). To assess such influences, demand for spatially explicit assessment of the potential climate change impact on and feedback from terrestrial ecosystems has emerged prominently (Prentice 1989; Cramer and Leemans 1993). This includes forested ecosystems, where significant ecological repercussions are projected due to climate change (Crookston et al. 2010). Climate change may interact with the plant species distribution (Iverson and Prasad 1998), vegetation composition, the structure of the plant community, ecosystem energy fluxes, gaseous exchanges, and water and nutrient cycles (Tchebakova et al. 2003). All these are highly complex and often nonlinear vegetation-climate interactions that respond in different ways to increased levels of climate change (Bonan 2016).

Lower-level ground vegetation, biomass allocation, net carbon uptake, and productivity at the ecosystem level are all inherently linked to climatic factors (Kumar et al. 2020). Vegetation interacts with the surrounding lands through the exchange of gases, nutrients, energy, and water (Pielke et al. 1998). Land-atmosphere interactions are regulated by the state of the land surface, which is governed in parts by various biological processes (Quillet et al. 2010). These processes depend on the local climatic conditions, which ultimately determine the vegetation type and its attributes (Pitman 2003). Accounting for about one-sixth of the annual exchange of carbon, and with a turnover time of 20 years, the terrestrial biosphere plays a pivotal role in the global carbon cycle (Prentice et al. 2001). The spatial or temporal variation in the terrestrial vegetation composition influences the momentum, energy flow, and hydrological cycle. Responses from vegetation at the ecosystem level manifest in the form of soil moisture, utilization of incoming solar radiation, CO_2 concentration, humidity, temperature, etc. All of these can be directly linked with the drivers of climate change (Bennett et al. 2005).

In the above-mentioned light, one of the biggest challenges in contemporary forest ecology is tracing and understanding the interactions between climate and vegetation that define the past, current and future response of vegetation to a changing climate (Scheiter et al. 2013). While vegetation processes generally take place on shorter time scales, addressing climate-vegetation interactions while tracing their potential impacts is a case of reconciling both temporal and spatial scales. Fundamentally, addressing this challenge requires modelling individual plant life cycles as influenced by plant traits and the environment. It is however hard to understand the responses solely based on theory or field experiments. Instead, a number of past and present research programs have been designed to address these challenges in an integrated manner. Advancing state-of-the-art dynamic vegetation models is often a central part of these research programs (Cramer and Leemans 1993). Such models are usually in the form of computer codes capable of integrating theory with the empirical knowledge from field experiments to simulate vegetation response to climate change (Kumar et al. 2018). Examples include novel dynamic global vegetation models (DGVMs), which have progressed from purely static equilibrium models to fully dynamic models (Cramer et al. 2001; Sitch et al. 2008). Vegetation models can be used to represent growth processes, simulate competitions, and describe environmental niches. They can also be used for mapping the development of vegetation under the influence of different external stressors and/or forcing. Such maps are important tools when assessing the impact of climate change on forests (Graetz et al. 1988) and biodiversity (Busby 1988). Maps are typically used as means of disseminating future model projections, for example, considering site-specific forest management interventions towards the expected impacts (Blasing et al. 1984; Cramer and Leemans 1993). In general, advanced modelling tools are nowadays widely used by forest ecologists for better understanding local ecosystems; they are also used for transferring scientific knowledge to different stakeholders and forest managers to use in decision-support systems. In the following, we present a holistic view of the basic approaches, principles, and applications of dynamic vegetation models for climate change impact studies with reference to forest ecosystems.

15.2 Approaches for Assessing the Impacts of Climate Change on Forests

Climate change impact assessment generally refers to the analysis of climate change-induced influences upon a given ecosystem such as forest ecosystems. Impact assessment on forests often addresses changes to the structure, composition, productivity, or other ecosystem traits (Parry and Carter 1998). While "climate change impacts" are often implicitly assumed to be detrimental, in practice some impacts represent beneficial factors, whereas others may have mixed consequences. Climate change impact assessments may be coupled with investigations of the adaptive response, which help to distinguish the gross (unmodified impacts) and net impacts (residual impacts after adaptive measures have been considered) (Feenstra et al. 1998). Climate change occurs at a global scale, and it is not practically possible to conduct large-scale experiments in a controlled environment. To overcome this

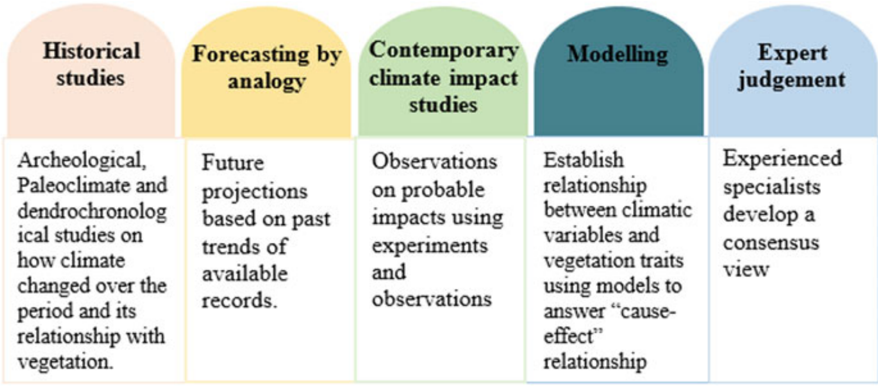

Fig. 15.1 Various approaches for studying the impacts of climate change on forest vegetation

limitation, various tools and methods have therefore been developed for evaluating the impact of climate change on vegetation processes. These available methods can broadly be classified into five categories, namely, (a) historical studies, (b) forecasting by analogy, (c) contemporary climate studies, (d) modelling, and (e) expert judgment (Fig. 15.1).

Historical studies use proxy-based methods to extract information and data from sediments, tree rings, and rocks. These studies implicitly take into account factors that promoted resilience to climate change in the past and one can use that knowledge to understand the present (Burke et al. 2021). **Contemporary studies** are characterized by relying on long-term observational records (obtained using state-of-the-art techniques), and they are sometimes used together with paleoclimatic reconstructions, for example, representing past (unmodified) climates (Mokhov 2019). **Analogue methods** take advantage of historic climate records and their observed consequences as means of indicating future developments. Such methods are especially valuable when replication of natural experiments is not possible in a controlled environment. Alternatively, "space-for-time" analogues may be used to study the expected future conditions at a certain location using an analogue site in a different location, where the current climate conditions are similar to the projected ones at the original site. The **expert judgement method** utilizes the expertise of scholars with advanced knowledge in the field. These findings can be accurate but evidently lacks a specific scientific methodology, thereby making the results harder to justify.

Out of all of these approaches, vegetation **modelling** is arguably the most frequently used for climate change impact studies. Vegetation models can help to answer the twofold question of: (a) how severe the effect will be on ecosystems and (b) when changes will be significant and visible, and offer explicit spatiotemporal information. Modelling approaches inherently rely on our current (imperfect) knowledge and generally make a number of process assumptions, which can compromise their ability to represent natural systems realistically (Feenstra et al. 1998).

Sensitivity studies and varying key model parameters represent one way to qualify the output from vegetation models. Overall, uncertainties stemming from different sources, that is, scenario (climate) uncertainty, model uncertainty, statistical uncertainty, internal variability, etc. must however be carefully considered when interpreting the output. For this aim, historical records are often used for the validation of vegetation models. If a model is able to reproduce past conditions successfully, it is often assumed that it will hold for future projections too. Then again, since systematic records are frequently scarce if not wholly unavailable, one needs to account for the associated uncertainties, which may be significant. Secondly, these types of studies are correlative studies. Hence, the underlying assumption that model skill in the past ensures model skill in the future, strictly speaking, implies that future climate variations and the realized impacts on forests are within the range of climate variations experienced in past.

15.3 Climate Change and Vegetation Feedbacks

Regional climate may be defined by the distribution of regional weather conditions based on long-term observations (Houghton et al. 1990). Like weather, climate characteristics are expressed by physical quantities such as sunshine hours, energy flux, precipitation, wind flow, etc. However, unlike weather, climate variables are essentially statistics, for example, the average energy flux, mean wind, or precipitation extremes exceeding the 90th percentile. In a stationary climate, the distribution of these quantities defines the natural (internal) variability and the probability of occurrence for specific events. Long-term climate fluctuations may induce significant changes to these distributions both in terms of shape and intensities and generally is a process taking place over long time spans (Berger 1960). The consequences of climate variability on ecosystems may be expressed in various ways such as changes in the seasonal cycle influencing the behavior of living creatures or their ability to sustain themselves. Some long-term climate fluctuations are the direct result of internal processes reflecting interactions between elements of the Earth system such as the atmosphere, oceans, ice cover, and vegetation. In contrast, here when referring to "climate change," we mean changes induced by the recent anthropogenic emissions of greenhouse gases, which are unprecedented in human history, and have led to global warming.

Complex nonlinear relationships exist between many of the components of the Earth system. Some of these nonlinearities are exhibited by phenomena at various levels influencing the global carbon cycle, such as soil processes and terrestrial biosphere storage capacity (Gerber et al. 2004). The global carbon cycle drives climate feedbacks in multiple ways. Whether the influence of increased CO_2 for a long time will have a positive or negative impact on vegetation is unclear (Quillet et al. 2010). However, it is certain that climate feedbacks from vegetation and soils on time scales from decades to centuries play important roles for both the local and global climates.

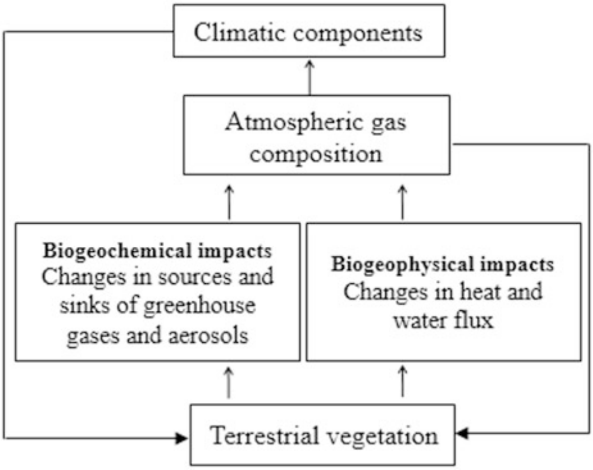

Fig. 15.2 Feedback loop between climate and terrestrial vegetation

Climate change has already had strong effects on the land biota accounting for increased species' extinction rates, change in reproductive timings, alteration in the plants' growth cycle, and modification in species' habitat distribution (He et al. 1999). Changes in important climatic factors such as average temperature and annual precipitation have resulted in irregularities in the nutrient cycle, microbial activity, carbon uptake, etc., which affect plant physiological processes. Altogether, the amalgamated effect of increased atmospheric CO_2, elevated global temperatures, and long-term alteration in precipitation patterns represent a swift and unprecedented change to the fundamental drivers of biogeochemical processes within ecosystems (Amundson and Jenny 1997).

Vegetation, acting as a source and sink for atmospheric carbon, plays a pivotal role in the climate system (Arneth 2015). In turn, forest ecosystems, being intrinsically dynamic, are constantly predisposed to climatic variations. These variations have a direct impact on the forest by altering its processes (Breshears et al. 2005) and indirect impacts by amplifying disturbances and endemic stresses (Brown and Wu 2005; Biagini et al. 2014). Climate processes dominantly control the spatial distribution, overall composition, and productivity of terrestrial vegetation along with alterations in soil or topography (Brovkin 2002). Conversely, vegetation affects climate through changes in biogeophysical mechanisms and biogeochemical effects. These interactions between forests and regional climate systems comprise feedback loops (Fig. 15.2). That said, the mechanism underlying these interactions is still not explicitly understood. Progression in plant physiology has simplified some mechanisms such as photosynthesis at the leaf and plant level, but the processes at a larger scale such as plant succession and competition are poorly explored (Peng 2000). The long life span of trees is one of the obvious hurdles for exploration. Alteration in soil profiles in response to vegetation change is even slower, thus it takes thousands of years to reach an equilibrium between ecosystem and environment (Brovkin 2002). In contrast, the availability of systematic observation of changing vegetation and soil is only up to several hundred years.

Terrestrial vegetation systems naturally adapt to environmental changes, but the pace of ongoing climate change surpasses the rate at which they can adapt and reestablish themselves (Busing et al. 2007). These alterations are taking place at large scales and are exacerbated by the increasing demand for food and other forest products (Arneth 2015). The forest produces ecological, social, aesthetic, and economic services including asylums for biodiversity, spiritual needs, medicine, and forest products (Hassan et al. 2005; Olokeogun and Kumar 2020). These services depend on the interactions between biotic and abiotic components of the forest ecosystem. To mitigate the consequences of climate change and ensure a continuous supply of goods and ecosystem services, ecosystems engineering is required. To engineer a system, mastery of its physical understanding is a prerequisite. Such understanding may be demonstrated through models that attempt to elucidate processes and linkages of the biosphere and climate (Kumar et al. 2020).

15.4 Modelling Forest Ecosystems

Understanding the interactive role of the biosphere and climatic system is important for coping with the planetary changes we currently experience. Forest ecosystem models are essential tools for investigating these complex interactions (Kumar et al. 2018). An ecosystem model inherently attempts to capture the most essential processes and linkages and simplify the underlying principles of local systems (Haefner 2005). The development of complex models relies on state-of-the-art knowledge about forest ecosystem processes and their relationship with the surrounding environment. Such models provide a comprehensive representation of natural systems and can be used to test new hypotheses (Kumar et al. 2018). However, for conserving and managing natural resources, the foremost use of such models lies in their predictive power. Complex process-based models are used widely for predicting the productivity, energy fluxes, and species composition based on climatic, edaphic, and topographic drivers. As mentioned above, forest ecosystem models validated for contemporary environments are frequently used to predict the future state of terrestrial ecosystems (Pickett and Kolasa 1990). In this framework, the future state of terrestrial vegetation is assessed based on a specification of an initial state by means of a set of equations and probability distributions for key ecological variables (Carpenter 2002). The models converted into software codes and computer programs are referred to as “simulators,” which are useful for calculating scenarios and visualizing the results (Pretzsch et al. 2008). Simulation-based vegetation models describe the linkages and relationship between ecosystem components and their functioning (Kimmins 2008), and they predict the change in state variables owing to forcing processes in the forest landscape (Brang et al. 2002). The capabilities of simulation-based vegetation models have long been explored by the research community, including a means of gaining and transferring knowledge to concerned stakeholders (Vacchiano et al. 2012).

Table 15.1 Description of different families of models with their characteristics

Families of Models	Characteristics	Example	Reference
Empirical models	• Statistical stand model • Site-specific applicability • Do not take climate change into account	Yield table, CAPSIS	Vacchiano et al. (2012)
Gap models	• Include prevailing growth conditions at the site (small area) and climate drivers for predicting vegetation composition • Lack determined vegetation shift • May inherit physiological base but for small patches only	CENTURY, BIOME-BGC	Bugmann (2001)
Hybrid	• Combination of long-term measurements • Also available as single tree management models	3PGs model	Kimmins (2008)
Dynamic global vegetation models (DGVMs)	• Process-based models • Derive the behavior of an ecosystem from a set of drivers and their interactions • Capable of predicting shifts in vegetation	IBIS, LPJ, JULES	Prentice et al. (2007)

The first attempt at establishing the relationship between climate and vegetation was taken through Koppen's climate classification system (Brovkin 2002). Later the simplicity and use of an ecophysiology basis for prediction led to the widespread use of the BIOME model (Prentice et al. 1993) for simulating the response of vegetation to climate change. Earlier classes of models comprise statistical models that quantify the relationship between the growth data of certain species and their associated environment. Based upon the principles and philosophy of method development, different model types have often been categorized into statistical models, empirical models, gap models, bioclimatic models, plant functional type models, ecophysiological models, biome models, biogeochemical models, and process-based models (Pretzsch et al. 2008). The newest generation of process-based models simulates the underlying physiological processes of plants and their interactions with climate and biotic factors leading to vegetation change. Examples of different families of models are given in Table 15.1.

15.4.1 Process-Based Models

Process-based vegetation models are mechanistic in nature (Kumar et al. 2018). The observations related to various growth processes and physiological characteristics of plants may be described by a numerical code, constructed to represent real environmental conditions to an acceptable extent. Each process is a self-contained module, and all of these distinct modules combine to build a model. Models use a set of components and their interlinkages to simulate the behavior of a forest ecosystem (Mäkelä et al. 2000). They are primarily directed towards understanding relationships between vegetation and the climate (Korzukhin et al. 1996). Process-based models use physical and mechanistic processes for driving systems behavior. These models may be regarded as analogues of real systems. Vegetation models at the operational scale are capable of simulating the growth and yield of a single stand and also the global-scale processes. Process-based models focus on matter allocation based on uptake and loss processes governed through environmental conditions (Pretzsch et al. 2008). Some process-based models use the light use efficiency approach, which estimates the conversion efficiency of absorbed photosynthetically active radiation (APAR) into productivity (McMurtrie et al. 1994; Running et al. 2004). They generally integrate biogeophysical, biogeochemical, biogeographical, and disturbance sub-models. These models simulate various plant and soil physiological processes spinning from bare earth to equilibrium and establish initial values for various carbon and nitrogen pools (Running et al. 2004).

To examine the vegetation distribution and its relationship to climate, biogeography models were developed (Prentice et al. 1993). These models simulate local vegetation patterns and distributions and the effect of different climatic regimes on them (King and Neilson 1992; Sykes and Prentice 1995). The biogeochemical models are applied to enhance the understanding of the flow of nutrients and carbon within and between vegetation and soil. They are primarily used for simulating vegetation productivity and carbon flux (Waring and Running 2010). These models work on prescribed vegetation and soil type to evaluate the pattern of productivity, carbon storage, and nutrient cycle (Foley et al. 1996; Rawat et al. 2020). Process-based biogeochemical models simulate seasonal development (phenology), photosynthesis, respiration, stomatal conductance, allocation of nutrients, and accumulation of organic matter in the soil (Cramer et al. 2001). In addition to this, models also calculate the soil water budget to account for water stress on plant productivity (Brovkin 2002). Terrestrial biogeochemical models have also been applied for examining the consequence of climate-induced vegetation change on biogeochemical processes (Peng 2000). Such assessment through exploiting the capability of vegetation models helps to understand the feedback of climate change on these processes and ultimately can aid to assess the impacts of climate change on vegetation (Foley et al. 1996).

Still, many key plant-environment relationships and processes are inadequately dealt with within these suits of process-based models. To this end, efforts have been made to link land surface processes and terrestrial biogeochemical processes in the present generation of process-based models (Bonan 1995; Haxeltine and Prentice 1996). Limitations of earlier models (static equilibrium state models) have been overcome using new generations of process models for understanding the consequences of anthropogenic climate change that are time-dependent; such models are often referred to as dynamic models. Such models are still in their embryonic stages (Foley et al. 1996; Peng 2000, Kumar et al. 2019a, b).

15.4.2 Dynamic Global Vegetation Models

Dynamic global vegetation models (DGVMs) are the latest addition to the family of process-based models. Having come into existence during the 1990s, DVGMs integrate independently existing modelling approaches for land-atmosphere interaction, vegetation distribution, terrestrial biogeochemistry, and vegetation physiology and dynamics into a single framework (Prentice et al. 2007; Murray et al. 2013; Kumar et al. 2018). DGVMs fuse biogeochemical, biogeographical, vegetation dynamics, and disturbance models. The key processes represented in the models are (a) land surface processes that use the information on vegetation type and soil for simulating energy, water, and momentum balance, (b) physiological processes and carbon cycles based on the rate of photosynthesis and respiration to yield carbon flux and (c) dynamic vegetation states that are time-dependent, for example, productivity, biomass growth, competition, establishment, and mortality (Quillet et al. 2010).

DGVMs can simulate long-term vegetation dynamics in response to environmental change considering biogeographical limits of different vegetation types and terrestrial biogeochemistry. DGVMs simulate vegetation dynamics based on dynamic sets of equations that operate across different time slices (Cox 2001). It includes key ecological processes, such as biophysical and biochemical processes, species establishment, growth, species competition, mortality, and disturbances for simulating the transient response of terrestrial vegetation to climate anomalies (Cramer et al. 2001).

In simulating the response of climatic drivers, vegetation is described by their plant functional type (PFT) rather than as individual trees. The plants/trees are classified into PFTs based on the similarity of their phenology (e.g., deciduous, evergreen), leaf form, climatic preferences (tropical, temperate), etc. (Kumar et al. 2021). In the case of grasses, grouping is based on photosynthesis type (C3 and C4) and climatic conditions (tropic, temperate, tundra). Each PFT is characterized based on different phenology, nutrient or biomass allocation pattern, the magnitude of the different parts of a tree, mortality and establishment characteristics, light and water use efficiency, photosynthesis rate, etc. (Woodward and Cramer 1996). The typical structural outline of a DGVM is presented in Fig. 15.3.

In general, DGVMs rely on meteorological/climate data (i.e., precipitation, photosynthetic active radiation, temperature, humidity, etc.), soil properties, and land-use information for establishing growth and distribution patterns of vegetation under current and future climatic conditions. Various sub-models within DGVMs work on different time scales. On a shorter time scale, that is, minutes to hours, biogeophysical and geochemical processes of photosynthesis, respiration, and land-surface processes (e.g., latent heat, energy fluxes, soil moisture, and evapotranspiration) are calculated whereas processes such as phenology of plants and nutrition allocation are estimated on a day to weeks' time scale (Peng 2000). Geographical distributions, vegetation dynamics (e.g., species interaction, establishment, and mortality), and disturbance (fire, herbivory, etc.) are determined on month to annual basis. In DGVMs, the establishment and survival of PFTs are determined through simulating competitions for light and water along with suitable bioclimatic

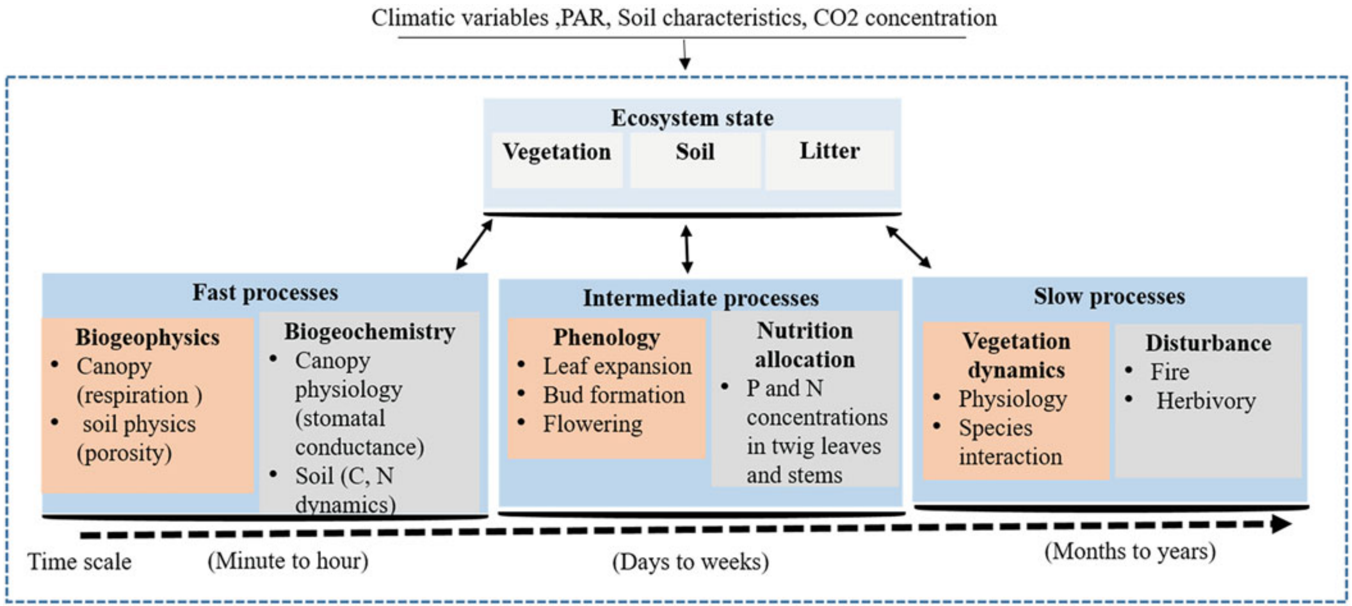

Fig. 15.3 Structural outline of dynamic global vegetation models (DGVMs) indicating different components and their respective time scales

limits, for example, monthly air temperature, minimum growing degree days (GDD), and amount of precipitation. Various outputs simulated by a DGVM include vegetation structure and distribution, surface fluxes of heat and carbon, soil respiration, gross primary production (GPP), net primary productivity (NPP), leaf area index (LAI), short and longwave radiations (incoming and outgoing), and CO_2 concentration. Initially, DGVMs require "spin-up" time for the vegetation to reach its realistic equilibrium state, from the bare ground (Peng 2000).

15.5 Applications of Vegetation Models

Vegetation models are widely used to simulate succession, establishment, and change in vegetation structure and composition (Bachelet et al. 2003). They are also increasingly used to study the climate change impact on vegetation and the associated feedbacks (Brovkin 2002) as indicated in Table 15.2. Such changes could for example be shifts in PFTs and/or the composition of vegetation structure (Smith et al. 2001). As already mentioned, vegetation models do not represent the complete range of complex and interlinked processes but are generally designed to be useful for specific applications. This includes decision support about the protection, conservation, and utilization of forest ecosystems within the framing of the sustainable development goals. In addition, the DGVM class of models (Table 15.2) is emerging as a powerful tool for studying vegetation behavior and associated biogeochemical

Table 15.2 Examples of dynamic global vegetation models (DGVMs)

DGVMs	Example applications	Authors
Lund-Potsdam-Jena (LPJ)	Estimated losses of carbon from wet tropical ecosystems (during the twentieth century, 39–49 PgC was released from deforestation, which is estimated to increase to158–243 PgC by 2100)	Cramer et al. (2004)
Five DGVMs (HyLand, LPJ, ORCHIDEE, Sheffield, TRIFFID)	All models simulate NPP reduction and decrease in soil residence time globally in the tropics and extra-tropics with respect to projected climate change	Sitch et al. (2008)
Integrated Biosphere Simulator (IBIS)	IBIS was used to assess the climate change impacts upon Indian forests for different emission scenarios. The model projected a shift in 39% of the forested grids under the IPCC A2 scenario and 34% under the IPCC B2 scenario by the end of the twenty-first century	Chaturvedi et al. (2011)
Joint UK Land Environment Simulator (JULES)	The influence of the leaf area index on the productivity of temperate forests was estimated. The study highlighted the limitations of the JULES leaf phenology model and suggested modifications for capturing the productivity of temperate forests more appropriately	Lee et al. (2019)

cycle (Scheiter et al. 2013) in the past, present, and future. Although still fairly simplistic, DVGMs have shown to successfully simulate several key processes robustly. DGVMs use the eco-physiological growth principle to model the distribution pattern for vegetation. They have the capability of adequately representing the land-surface energy and water budget (Bonan 2008). DGVMs use soil data along with climatic forcing data for simulating the state of ecosystem vegetation (Scheiter et al. 2013; Kumar et al. 2019a, b). DGVMs have been successfully used to explore the climate change impact on the carbon cycle and biome distribution (Cramer et al. 2001). Recent Earth system models link a DGVM to general circulation models (GCMs) and create a fully coupled biosphere-atmosphere model that can be used to assess the impacts of climate change on forests.

Although DGVMs could be used to address some of the most burning questions in current vegetation ecology, for example, with respect to climate variability and climate change effects on land ecosystems and their functionalities, they have so far primarily been used to study the carbon cycle and for estimating the response of vegetation to climate change (Eastaugh et al. 2011). Not all models are equally suitable for such studies since the intricacy and depiction of processes such as carbon cycling and nutrient allocation and canopy physiology notably vary among models (Foley et al. 1996).

15.6 Limitations of DGVMs

DGVMs were originally designed to merge vegetation distribution and ecosystem processes (Cramer et al. 2001). Different ecological processes operate at different spatial and temporal scales for which information might not be available. In general, DGVMs have problems in representing fine-scaled processes. This includes important processes such as photosynthesis, seed set, which are taking place at very fine time scales and therefore need to be empirically parameterized in DGVMs. That is, instead of detailed mechanistic simulation, empirical relationships are assumed to represent the processes (Lischke 2001).

Many inherently nonlinear climate-vegetation responses are not easy to represent within a model, and hence the typically simplified representations can lead to significant errors. Common limitations are linked to the relationship between the climatic forcing and key physiological processes that affect plant growth such as the rate of photosynthesis and respiration. Again, some of these interactions happen at sub-grid spatiotemporal scales that are not possible to represent explicitly, and which makes it difficult to define appropriate PFT classes and accordingly limits the scope for simulating the detailed impacts. In the same way, it is often not possible to simulate the effects of extreme climate events on vegetation like forest fires or storms, which are sometimes much more important than the gradual changes (Jentsch and Beierkuhnlein 2008). High-resolution and high-quality downscaled climate projections may not be available for certain regions, leaving only coarser scale information (Melton et al. 2020). In turn, this makes the task of assigning an appropriate PFT class to each grid point difficult as each cell may in reality represent a diverse agglomeration of trees. Models often represent the soil dynamics using simple soil models, which sometimes represents real processes with less accuracy (Kurz et al. 2008). Finally, some models do not have the capability to simulate disease and pest outbreaks, which like extreme climate events may have significant consequences and can strongly impact vegetation structure (Kurz et al. 2008).

15.7 Other Challenges and the Way Forward

DGVM simulations are becoming a key instrument for assessing the climate change impact on forests. However, as detailed above, the power of these tools is seriously curtailed due to a range of different factors, including model limitations, data availability, and uncertainties. Other constraints include inaccessibility of the model codes, lack of information about the internal structure of the model representing the various interlinked processes, proper model documentation, adequate calibration, validation, etc. The absence of long-term observation and inadequate harmonization of available data makes calibration and validation of models a difficult task (Borghetti and Ferrara 2010). To overcome these challenges, there is an urgent need to bridge the gap between the modellers and the scientific communities working with field-based monitoring. This includes increased use of ever more advanced remote sensing tools for delivering the desired information over various geographical and temporal dimensions.

In terms of advancing current vegetation and forest modelling tools, many existing state-of-the-art codes are more or less propriety to their development teams, and the lack of public access to the source codes limits the development of these codes, including broader testing and validation. Although open sourcing a model remains a developer's choice, it thus needs to be accompanied by adequate supplementary information and metadata for exploiting such model's efficiency and repeatability (Michener 2006). While reporting the result of models, proper validation of the output is also all too often missing (Refsgaard et al. 2014). Optimally, this should be based on multiple data sources, for example, field-based observations supplemented with remote sensing observations. The development of dedicated tools such as Bayesian calibration, resampling methods, and information theory could be helpful for model calibration, validation, and performance comparison (Arnold 2010).

Many existing forest models have been developed based on the available information from a specific location or region. Understanding the underlying processes in the model, therefore, becomes essential if one wants to avoid unwanted propagation of errors when applying the same model in a new region. To scale up or scale down a model's outputs, one must, for example, be aware of how hierarchical processes relate within a model to the occurrence scale. Lack of such understanding may result in unintended mistakes when upscaling or downscaling as part of estimating the climate change effects on forests exploring a modelling-based approach.

15.8 Conclusions

The fundamental question of "what the impact of climate change on forests will be" requires insight into the different processes comprising the forest ecosystem. In recent decades, a plethora of observational methods have evolved for studying the dynamics of terrestrial ecosystems such as the use of flux towers and remote sensing-based observations. Satellite observations attain a special status for large-scale process understanding as they provide comprehensive coverage of the landscape. Continued advancement of sensors is expanding this scope. But there are limitations as to what can be seen from space, for example, in terms of forest diversity and composition. Monitoring ecosystem development and functioning processes have become a priority for evaluating the effects of human management interventions and climate change. Due to the recent acceleration in anthropogenic forcing, there is an urgent demand for tools and methods for understanding forest processes and predicting the future risk to the forest from climate change and human activities. The development of DGVMs is largely a response to this urge. DGVMs provide a platform to explore and advance our current understanding of the causal relationships between terrestrial vegetation and their surrounding by linking the underlying processes with the behavior of forest ecosystems. DGVMs exploit the power of contemporary computing for predicting ecosystem processes on a global scale. Driven by historically developed knowledge from biosphere studies, vegetation models successfully yield a predictive description of the forest ecosystem. However, many questions linked to ecosystem processes remain unanswered; at the same time, many critical processes are still either overlooked or presented in a simple manner, necessitating the further improvement of vegetation models.

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Agroforestry Approaches in the Restoration of Peatland Landscapes in Central Kalimantan, Indonesia

16

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Abstract

Peatland is one of the important ecosystems in Indonesia, which covers about 14.9 Mha area. It has significant roles in carbon storage, water regulation, and biodiversity habitat. However, peatland has been degraded fast owing to overexploitation and massive canals development, which cause water drainage, subsidence, and carbon emission. Peatland restoration has become an important agenda in Indonesia to reduce fire risk and, at the same time, improve the resiliency of farmers by improving their livelihood. Sustainable peatland management systems have been applied by communities in the peatland landscape of Sebangau river and Kahayan river in Central Kalimantan, Indonesia. We identified tree-based agroforestry types been practiced in the peatland landscape of Central Kalimantan, such as jelutong tree-based agroforestry, agrosilvopastoral, agrosilvofishery, and apiculture system. All those agroforestry systems provide alternative livelihoods for farmers and improve peatland productivity. This chapter provides the performance of tree-based agroforestry types in Central Kalimantan. A patchy peat-swamp forest that still exists in the landscape

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provides habitats for natural vegetations and animals, which play important roles as pollinator and seed dispersal agents. Also, the existing forest provides sources for non-timber forest products.

Keywords

Ameliorant · Agrosilvofishery · Agrosilvopastoral · Peat water level · Peat Hydrological Unit

16.1 Introduction

Peatland is a wetland ecosystem, which is formed by the accumulation of organic matter in the basin under inundation conditions. Tropical peatlands are characterized by warm temperature, high precipitation, but low evaporation, which initiate persistent wet conditions on the soil surface. This situation inhibits microbial activities (Takada et al. 2015). The decomposition process in the anaerobic condition is usually slower than the accumulation rate. This process occurs in the peat-swamp forest, producing significant organic matter (Blackham et al. 2014; Noor and Masganti 2016). Based on water source and topography, peatlands in Indonesia is mostly categorized as *ombrogenous peat* (Takada et al. 2015; Noor and Masganti 2016), where the peatland is raised above the surrounding landscape and the water source is only from precipitation; hence it is nutrient-poor (Neuzil et al. 1993; Takada et al. 2015; Noor and Masganti 2016).

The peat ecosystem consists of three components: vegetation, water, and organic matter, which are arranged in a unit completely, and form balance, stability, and productivity. A peat ecosystem positioned in a basin between two rivers or between a river and the sea is called the peatland hydrological unit (PHU). The PHU as a landscape can be seen from the edge of a river perpendicular to the other river and one or more basins can be located in the core of the two rivers (Barus et al. 2009; BRG 2019). This is because the horizontal distance between the two large rivers is several tens of kilometers. At the edges is shallow peat, and moving towards the center of the dome, the surface of the peat soil gradually rises. The height of the peat dome varies; it can reach 3–8 m above river water level. On deep peat, the center of the peat dome can be 8–13 m thick; groundwater is stagnant and very nutrient-poor. Around the top of the peat dome or the edge is sloping peat, shallower and more mixed with minerals so that the fertility rate is higher (Noor and Masganti 2016). Peat soils in narrow basins are usually thin peat (0.5–1 m) to medium peat (1–2 m). The position of the first major river to the next major river will be found, respectively, a river embankment or levee, a backswamp, a basin containing peat soil. The highest topography has the thickest peat called peat dome, then a backswamp plain and a subsequent river embankment (see Fig. 16.1; Subagyo 2000).

Based on the Government Regulation of Indonesia (Government Regulation No. 71 of 2014 jo. Government Regulation No. 57 of 2016 on Protection and Management of Peatland Ecosystem; https://forestlife.id/workshop-on-peatland-

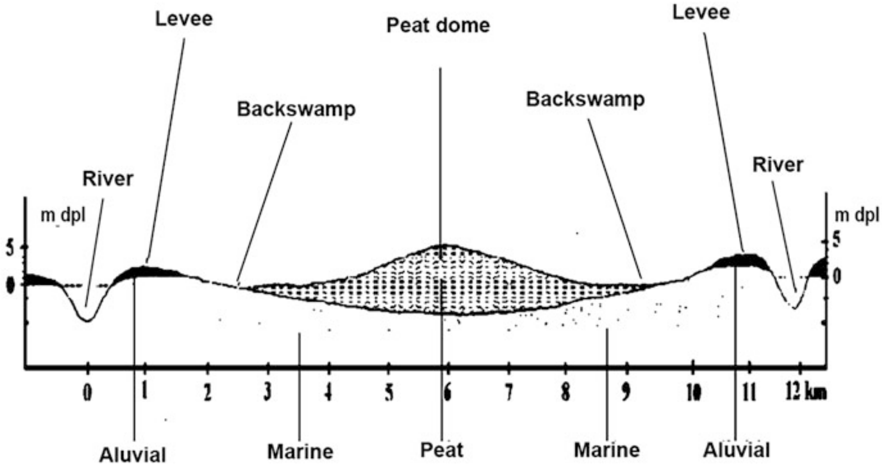

Fig. 16.1 Schematic cross section of a PHU between two rivers (Source: adapted from Subagyo 2000)

and-climate-change/), there are two functions of the PHU based on the peat depth, and those are protection and cultivation functions. The peat dome or peat depth deeper than 3 m is categorized as a protection function, while peat depth less than 3 m is a cultivation function for sustainable agriculture. However, the sustainability of agricultural practices on peatlands is threatened by over-drainage and fires (Suryadiputra et al. 2005; Wibisono et al. 2005; Surahman et al. 2018). To minimize the risk, agricultural system on peatlands should be developed as wise farming practices by considering the limiting factors of the peat ecosystem. Najiyati et al. (2005) suggested ten steps of developing sustainable agriculture on peatlands, such as: (1) identify and understand the type and behavior of peatlands; (2) utilize and organize land according to its typology without drastically changing the environment; (3) implementing a water management system that can guarantee soil moisture or avoid drought in the dry season and prevent flooding in the rainy season; (4) zero burning practice; (5) mixed farming by combining seasonal and perennial crops, livestock, and fish; (6) selecting plant types and varieties in accordance with land conditions and market demand; (7) using ameliorant materials, such as compost and manure to improve soil quality; (8) conducting minimum tillage in watery or moist soil conditions and zero waste; (9) using micro-fertilizers for seasonal crop cultivation; and (10) planting perennial crops in peatland, preceded by compaction and planting annual crops to increase soil-bearing capacity.

Developing a peat-friendly agriculture on peatlands is a challenge. Here, we propose an integrated farming cultivation system in a PHU without burning or producing waste, which meets the four principles of technically applicable, socially acceptable to local farmers. It is economically profitable and environmentally friendly (Surahman et al. 2018; Uda et al. 2020). The objective of this chapter is to describe various agroforestry models in peatland landscape which are present in levee, backswamp, and peat dome of the PHU of Kahayan and Sebangau river, Central Kalimantan. This has been used as agricultural and agroforestry practices for years and an integrated agricultural model for PHU management.

16.2 Agroforestry Landscape Analysis

Agroforestry is defined as a land management system based on sustainability, which increases overall land yield, combines the production of agricultural crops (including tree crops), forest plants, and/or animals simultaneously or sequentially on the same land unit, and applies management methods. According to the culture of the local population (King and Chandler 1978), interpretation of agroforestry is complex, between natural resource management through a combination of tree species on land and agricultural landscape and policy change required to secure the economic, social, and environmental benefits that can provide to various segments of society (Van Noordwijk et al. 2019). The relationship between peat ecosystems and agroforestry is that the peat ecosystem is a habitat and landscape with resources while agroforestry is an input system to produce benefit in the landscape (Mulatu and Hunde 2019; Plieninger et al. 2020).

Agroforestry landscape is a science that studies agroforestry systems at a landscape scale, where spatial and temporal aspects are very influential (Arifin et al. 2010). Agroforestry landscape study is different from agroforestry study that is generally carried out at the site or plot scale (Pastur et al. 2012). At the landscape scale, the land-use system usually uses ecological boundaries, such as watershed boundaries, peat depth, saturation level, period of inundation, the presence of a tidal effect, and others. The function of land use is related to the structure and biophysical condition (Arifin et al. 2010). In a PHU, the function of peatland use is determined by peat depth. The PHU protection and cultivation functions are carried out in an integrated and segregated approach (Zglobicki and Zglobicka 2012). Agroforestry landscape analysis can be assessed through interactions between objects and elements in the landscape and its impact. In the agroforestry landscape, each agroforestry type can be repeated at spatial and temporal scales (Pastur et al. 2012).

The discussion of the agroforestry landscape in this chapter cannot be separated from the discussion of the ecology of peatland landscape because agroforestry lands lie on a PHU. Agroforestry landscape consists of four main principles: (1) there is the heterogeneity of development and spatial dynamics, (2) there is the heterogeneity of interaction and exchange in the landscape, (3) there are effects on spatial and in biotic and abiotic processes, and (4) management of spatial heterogeneity (Arifin et al. 2010). These indicate that the characteristics of agroforestry landscapes emphasize the relationships among types of agroforestry practice, processes, and scale. Agroforestry landscapes also consider ecological flows in the mosaic of agroforestry landscapes, land use and land cover change, scale, and other ecological processes. This includes the conservation landscape and preserving its ecosystem (Pastur et al. 2012; Plieninger et al. 2020).

Agroforestry landscapes look at how spatial planning affects the abundance of organisms at the landscape level, the behavior and functions of organisms from a landscape to the entire ecosystem. It is also emphasizing the anthropogenic impacts on the landscape's structure and functions. Landscape functional units can be evaluated both qualitatively and quantitatively in the context of agroforestry (Arifin et al. 2010; Dewi et al. 2017).

16.3 Landscape Characteristic of the PHU of Kahayan–Sebangau River

The PHU of Kahayan–Sebangau river is located in two districts of Katingan and Pulang Pisau, Central Kalimantan. It covers 451,507 ha (MoEF 2017), while the total peatland area is about 67% of the total PHU area (BRG 2017). The peatlands in this area are predominantly located in the freshwater swamp zone and partly in the tidal swamp zone. A schematic cross-section illustration of the PHU is described in Fig. 16.1.

Based on soil nutrient or soil fertility level, most of the peat soil of the PHU of the Kahayan–Sebangau river is classified as oligotrophic peat. This type of peat is acidic and poor in nutrients and is generally found in the backswamp and peat domes of the PHU. Meanwhile, peat in the small and shallow basins is classified as eutrophic peat, which is relatively more fertile because it is enriched with nutrients and sediment from rivers brought in every time a seasonal flood occurs (Takada et al. 2015; Noor and Masganti 2016).

Agricultural development on the PHU of the Kahayan–Sebangau river depends on the characteristics of peatlands. Most peatland area is not suitable for agricultural development, because of some limiting factors, which consists of seasonal flooding or inundation, the thickness of peat, very acidic and very low nutrient content of peat soils (Ritung and Sukarman 2016).

Kalampangan is a transmigration village laid on peatland, at 20°16′00″–20°19′20″S and 113°58′20″–114°03′50″E. The village is located administratively in Sabangau subdistrict, Palangkaraya city, Central Kalimantan province (Fig. 16.2). Kalampangan covers an area of 5000 ha with a flat topography (slope of 0–3%) and an altitude of 14–18 m above sea level (asl). The soil type of Kalampangan consists of humic gley soil and Histosol. The wet season occurs from November to February and the dry season from June to September (Kalampangan 2018).

The Kalampangan village's peatlands state within the PHU of the Kahayan–Sebangau river is one of heavy settlement and agriculture. Since the transmigration program began years ago, the peatlands have been drained. The presence of a number of drainage canals in the form of one principal canal, which also serves as an area boundary with Kameloh village, as well as a number of minor and tertiary canals, demonstrates this (Fig. 16.3). Apart from those three canals, there is also a quaternary ditch locally known as "parit cacing" in farmers' farm (Fig. 16.3d). It has narrower dimensions of 30–40 cm in width and depth.

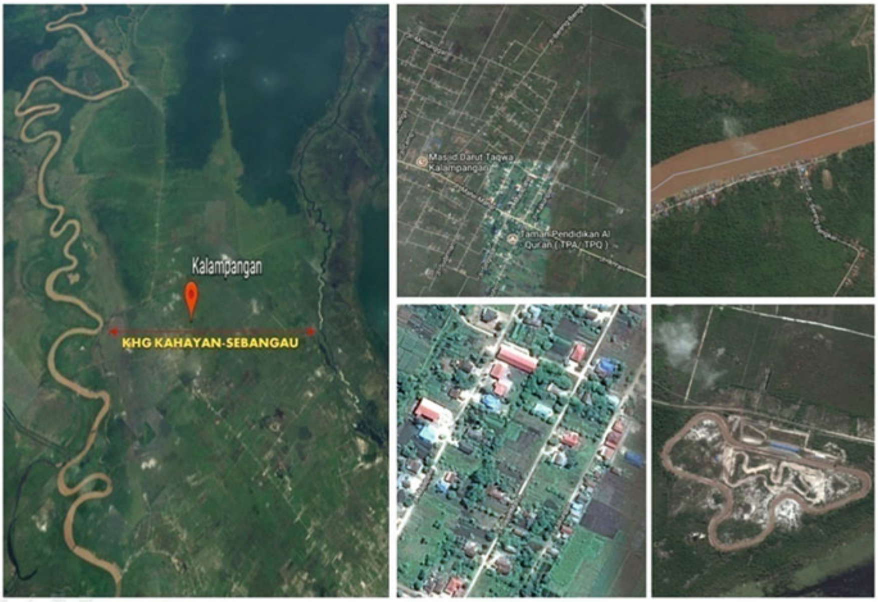

Fig. 16.2 Kalampangan village in the PHU of Kahayan–Sebangau river

16.3.1 Agroforestry Landscape of the PHU of Kahayan–Sebangau River

In the PHU of the Kahayan–Sebangau river, farmers applied various types of agroforestry depending on the physiographic unit of the peatland (river embankment, backswamp, and peat dome). The agroforestry system developed by farmers in Kalampangan village can be classified into six categories, namely: (1) agroforestry with four cropping patterns; (2) agrosilvofishery with three cropping patterns; (3) silvopasture with three cropping patterns); (4) agrofishery with one cultivation pattern; (5) apiculture with two cultivation patterns; and (6) agropasturesilvofishery. The composition of the components of each of these systems is described in Tables 16.1, 16.2, and 16.3.

16.3.1.1 Agroforestry in the Levee Area

Local farmers develop two agroforestry systems in the river embankments, namely, agrosilvofishery and agrofishery (*beje* pond). One of the typical agrosilvofishery systems in this area is a dike pond. The embankment pool technique is carried out to overcome the high tide water higher than 2 m. The pond embankment height is 4–5 m, with the width of the embankment 1.5–2 m. The size of the embankment pool is 10–15 m wide and 20–50 m long. The embankment is usually combined with a *beje* pond. Local farmers planted the embankments with several seasonal crops and tree species. The tree species used to strengthen the pond embankments are *Shorea*

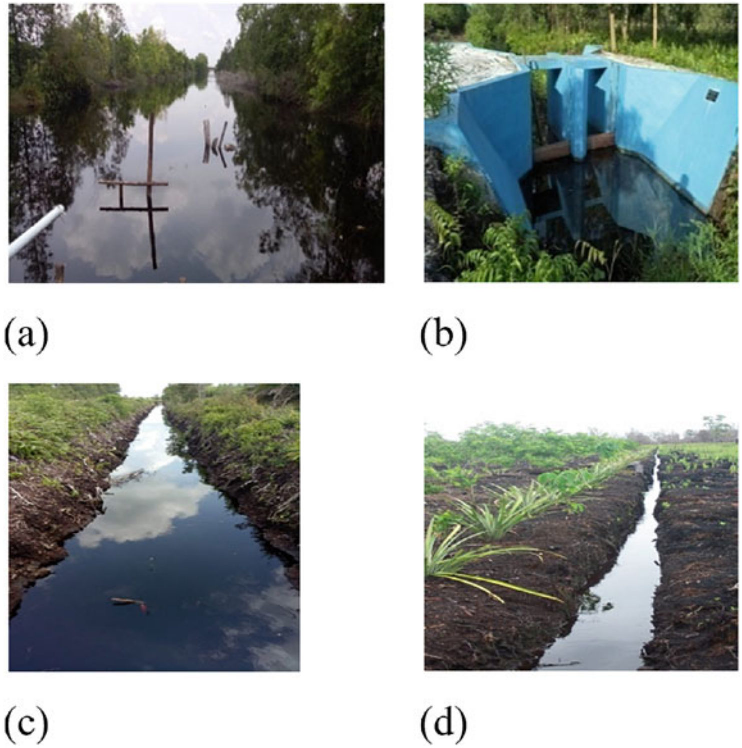

Fig. 16.3 Three types of canal types based on their dimension. (**a**) primary canal, (**b**) secondary canal, (**c**) tertiary canal, (**d**) quaternary ditch (parit cacing)

balangeran (kahui) and *Nauclea orientalis* (bengkel). Some vegetation is also planted on embankments, such as bananas, pineapples, rambutan, soursop, guava, and *Mangifera odorata* (kueni). Other than that, other seasonal plants such as red chilies, *Sauropus androgynus*, and cassava are also planted on the embankments. Some fish are cultivated in the pond (Table 16.1).

Another traditional agrofishery practiced by farmers is called *beje*. Beje is a rectangular pond, which is developed in a river embankment (levee) as shown in Fig. 16.4. The size of the *beje* varies from 10–30 m long, 5–10 m wide, and a water depth of 1.5–2 m. Each side of the *beje* pond is connected with a canal called "tatah" or "pelacar" in the local language. *Tatah* or *pelacar* aims to channel fish from the canal into the *beje*. A beje may contain 5–11 fish species, which is dominated by swamp fish (blackfish). The water plants that are kept in beje are water spinach, water hyacinth, and *Azolla pinnata*. *Azolla pinnata* and water hyacinth are used for fish feed and compost. Fish is harvested in the dry season when the water level in the beje is 20–30 cm lower than the surrounding land surface. One rectangular *beje* pond in size of 50–250 m^2 produces fish between 128–1745 kg with an average of 879, 9 $\pm$ 83.60 kg fish/beje/year. Beje is a productive fishery business that can

Table 16.1 Agroforestry types on the levee in the Kalampangan village

S. no.	Agroforestry system	Plot level design	Components of vegetation and fish
1.	Agrosilvofishery	Embankments are built 4–5 m high, 1.5–2 m wide, embankment pool size: 10–15 m wide, 20–50 m long.	Embankment (tree) terrace reinforcement plants. Fruit crops: banana, soursop. Seasonal crops: *Sauropus androgynus*, red chilies, *Ipomoea aquatica* (water spinach), cassava. Types of fish: *Channa striata* (gabus), *Anabas testudineus* (papuyu), *Trichopodus tricopterus* (sapat siam), *Cyprinus carpio* (karper), and catfish (*Clarias batrachus*).
2.	Agrofishery (*beje* pond)	Built at tidal locations on the banks of rivers or primary canals. Size: 3–5 m wide, 10–20 m long, 1.5–2 m deep. During the rainy season, it is flooded. Fish are harvested during the dry season.	Water plants: Water spinach, water hyacinth (*Eichhornia crassipes*), and *Azolla pinnata*. Types of fish: Papuyu, gabus, *Channa pleurophthalma* (kerandang), catfish, sapat siam, Wallago Attu (tapah), *Kryptopterus bicirrhis* (lais).

contribute to local farmers' annual income around IDR 650,000 to 7,900,000 (or USD 46.4 to 564.3) per beje.

The limiting factor for fish cultivation in the river embankments is waterlogging. Local farmers develop embankment pools to tackle this problem. They also make *beje* ponds and floating agriculture. Another obstacle to fisheries in Kalampangan is the high price of factory-made fish feed. The solution to this problem is to self-provide fish feed from local ingredients, such as water hyacinth leaves, *Azolla pinnata* leaves, taro leaves, snails, maggot, etc.

16.3.1.2 Agroforestry in the Backswamp

Agroforestry types in the backswamp in Kalampangan village differ from the levee. We found four types of agroforestry, which is summarized in Table 16.2. Some pictures of agroforestry in the backswamp are shown in Figs. 16.5 and 16.6.

First, the agro-silvicultural system (agroforestry) has four cropping types, namely: (a) the paddy fields on the edge of the land are planted with wood and banana trees. Vegetables are planted on the embankments of the paddy field, combined with *Paraserianthes falcataria* (sengon) trees. Vegetable crops and fruit trees are also planted. (b) Alley cropping with a split-plot technique. Woody trees are planted at a spacing of 6 × 7 m, 5 × 4 m, 5 × 3 m. In the alley that is formed between two tree lanes planted with seasonal plants (vegetables). Some timber trees are planted, such as *P. falcataria*, *Aquilaria malaccensis* (gaharu), *Hevea brasiliensis* (rubber tree), *Dyera polyphylla* and *Elaeis guinensis* (oil palm), and mixed with

Table 16.2 Agroforestry types in the backswamp in the Kalampangan village

S. no	Agroforestry system	Plot level design	Components of vegetation, fish, livestock
1.	Agrisilviculture	The rice fields on the edge of the land are planted with wood and banana trees. Vegetables are planted on the embankments.	Wood plants: Sengon. Vegetable crops: Chilies, leeks, mustard greens, eggplant and long beans. Fruit crops: Bananas, taro, cassava.
		Alley cropping with a split plot layout technique. Wood plants are planted at a spacing of 6 × 7 m, 5 × 4 m, 5 × 3 m. In the alley formed between two tree lanes, seasonal crops (vegetables) are planted.	Timber crops: Sengon, *Aquilaria malaccensis* (gaharu), rubber, marsh jelutong and oil palm. Seasonal crops: Corn, mustard greens, eggplant, kale, spinach, green onions, and chilies.
		Wood plants are planted around the land as a fence. Vegetable plants are planted in the core area.	Wood plants: *Dyera polyphylla*. Vegetable crops: Corn, chilies, mustard greens, groundwater spinach and eggplant.
		The land is divided into two blocks. The first block is for seasonal crop cultivation. The second block is for tree cultivation or is allowed natural regeneration.	Timber plants: Sengon (*P. falcataria*), *D. polyphylla*, *C. rotundatus* (tumih), *A. mangium*. Seasonal crops: Dragon fruit, corn, chilies, taro and mustard greens. Fruit crops: Rambutan, pineapple.
2.	Agropasturesilvofishery	Alley cropping with a split plot layout technique. The size of the trench around the land: Width 40–50 cm, depth 40–50 cm. There is a tarpaulin pond for fish farming between two tree trails. Pool size: 10 cm long, 3 m wide, 1.5 m deep. There is a cow pen.	Wood plants: *D. polyphylla*. Vegetable crops: Corn, chilies and sweet vegetables (mustard greens). Type of fish: Catfish. Type of livestock: Cow.
3.	Apiculture	Bee colony boxes are placed in the yard. In the yard, a number of bee food sources were planted (pollen and nectar).	Types of honey bees: *Apis melifera, Apis cerana* and *Heterotrigona itama* (kelulut) stingless bees. Food sources for bees: Corn, spinach, dragon fruit, calliandra, sunflower, passion fruit. Sap source plants for *H. itama* bees: Jackfruit, *D. polyphylla*.

(continued)

Table 16.2 (continued)

S. no	Agroforestry system	Plot level design	Components of vegetation, fish, livestock
4.	Agrosilvopastoral	Jelutung (*D. polyphylla*) is planted with a spacing of 5 × 5 m. In the passage between the two tree lines, annual crops are planted. On the edge of the land is planted with fodder grass.	Wood plants: *D. polyphylla, S. balangeran*, agarwood. Seasonal crops: Corn, chilies, kale, spinach and mustard greens. Hedgerows: Elephant grass. Livestock: Cows, goats.
		Jelutung species are planted at 5 × 5 m spacing. There are seasonal plants. In the middle of the land, a swallow's nest is built	Perennials: Jelutung, aloewood. Seasonal crops: Corn, chilies and green onions. Livestock: Swallow.

seasonal crops, such as corn, mustard greens, eggplant, kale, spinach, green onions, and chilies. (c) Timber trees (*D. polyphylla*) are planted around the land as a fence, and vegetable crops (corn, chilies, mustard greens, groundwater spinach and eggplant) are planted in the core area. (d) The farm is divided into two blocks. The first block is cultivated with the seasonal crop, while the second block is planted with timber trees, such as sengon, *D. polyphylla*. Other tree species, such as *Combretocarpus rotundatus, Acacia mangium*, are not planted, but they regenerate naturally. The farmers also plant seasonal crops (such as dragon fruit, corn, chilies, taro, and mustard greens) and fruit crops (*Nephelium lappaceum* and pineapple).

The second is agropasturesilvofishery. This system combines the cultivation of agricultural crops, cattle, fish farming in tarpaulin ponds, and tree crops (*D. polyphylla*) in one land unit. The cropping pattern and land arrangement were carried out using alley cropping techniques with the split-plot arrangement technique. The size of the trench around the land is 40–50 cm wide and 40–50 cm deep. There is a plastic pond for fish farming between two tree trails, 10 m long, 3 m wide, 1.5 m deep (Fig. 16.7). Species of cultivated fish are catfish and papuyu. *D. polyphylla* is mixed planted with vegetable crops, such as corn, chilies, and sweet vegetables (mustard greens). Also, farmers raise cattle on their farm. At the boundary of the land is planted with fodder grass.

Some farmers in Kalampangan currently practice apiculture or honey bee cultivation (Fig. 16.8). Apiculture is beneficial for farmers who do not have their own land as this forms a source of income. It is also beneficial for cultivated plants, as they help pollination and act as biocontrol of ants, flies, and other beetles that can damage flowers and fruits. Thus, it can increase plant productivity. The main obstacle to developing honey bee cultivation is the use of pesticides, which may kill bees. This obstacle can be overcome by planting ornamental plants, such as sunflowers, *Antigonon leptopus*, and calliandra plants, as the source for pollen and nectar.

Fourth, agrosilvopasture. In this system, the land is used to cultivate agricultural crops, tree crops and forage crops (Fig. 16.9). There are two types of

Table 16.3 Characteristics of the agrisilviculture, agrosilvopastoral, silvopastoral, and apiculture systems in the peat dome of PHU Kahayan–Sebangau in the Kalampangan village

S. no	Agroforestry system	Plot level design	Components of vegetation, fish, livestock
1.	Agrisilviculture (Wanatani)	Seasonal plants are planted in an alley formed from two rows of *D. polyphylla* plants. The spacing used was: 6 × 7 m, 5 × 3 m and 5x5 m. at the edge of the land boundary, a drainage ditch 40–50 cm wide and 40 cm deep is made around the land. The drainage ditch will be connected to a tertiary channel. On the inside, a ditch or "parit cacing" is made, which divides the land into plots of plant locations.	The constituent components: (1) tree species: *D. polyphylla, Aquilaria malaccensis*, durian; (2) types of fruit plants: rambutan, papaya, soursop, orange, pineapple; (3) types of seasonal crops: Corn, cassava, chilies, eggplant, mustard greens; (4) types of shade plants: *Ceiba pentandra*.
		The land is divided into two blocks. The first block is for seasonal crop cultivation. The second block is for tree cultivation or is allowed to become forest for timber harvesting (natural succession).	Wood plants: Tumih and jelutung. Seasonal crops: Corn, chilies, mustard greens and green onions. Fruit trees: Rambutan, pineapple.
		Trees are planted around the cultivated land (fence system). Trees serve as shade and windbreaker.	Wood plants: Jelutong, aloewood. Seasonal crops: Corn, chilies, mustard greens and green onions.
2.	Agrosilvopastoral	Swamp jelutong planted with a spacing of 5 × 5 m. in the passage between the two tree lanes, annual crops are planted. The edge of the land is planted with fodder grass.	Perennials: Marsh jelutong. Seasonal crops: Corn, chilies, green onions and mustard greens. Fruit / tuber crops: Taro, cassava and rambutan. Hedgerows: Elephant grass. Livestock: Cows, goats.
3.	Silvopastoral	*D. polyphylla* trees are used for duck farming and goat grazing. The advantage: Jelutongs free from weeds and get fertilizer from livestock manure. Jelutong trees are also used for swallow cultivation. Swallow droppings can be used as organic fertilizer (ameliorant) after fermentation.	The constituent components: (1) tree species: *Dyera polyphylla, Aquilaria malaccensis*; (2) types of fruit plants: Rambutan, pineapple; (3) types of seasonal crops: Corn, cassava, chilies, eggplant, mustard greens; (4) livestock: Broilers, ducks, swallows, cows and goats.
4.	Apiculture	Bee colony boxes are placed in the yard. In the yard, a number of bee food sources were planted (pollen and nectar).	Types of honey bees: *Apis melifera*. Food sources for bees: Corn, spinach, dragon fruit.

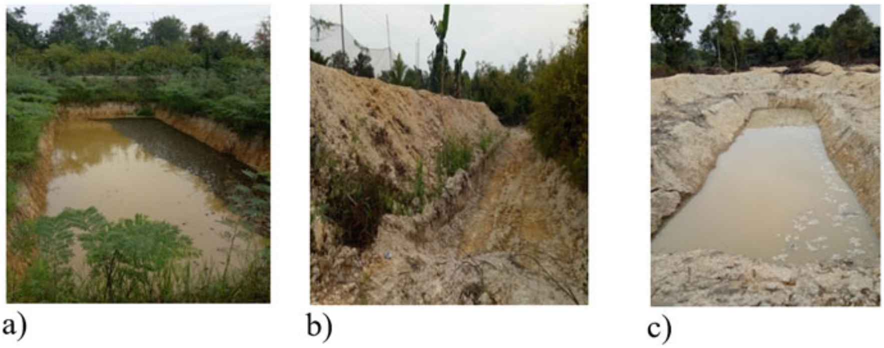

Fig. 16.4 Profile of the agroforestry system in the embankment area. (**a**–**b**) Embankment pool, (**c**) beje pond

Fig. 16.5 Agroforestry in the backswamp. (**a**–**b**) Combination of rice field and *P. falcataria* trees, (**c**) alley cropping of *D. polyphylla* species with cassava

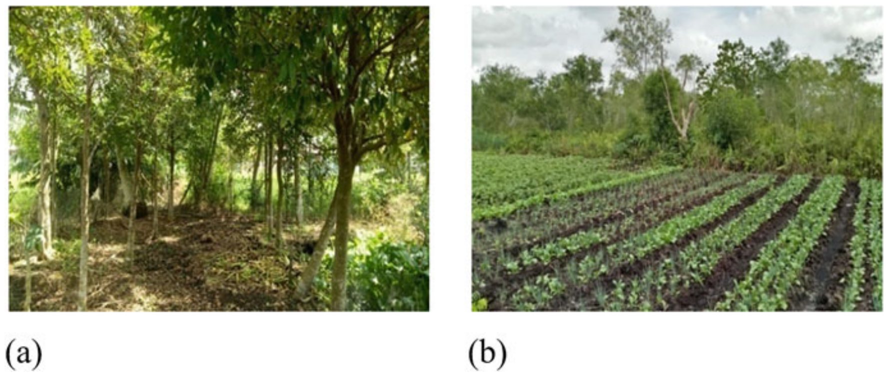

Fig. 16.6 Agroforestry system in the backswamp. (**a**) Timber trees around the land as a hedge. (**b**) Separate blocks of seasonal crops and timber trees

Fig. 16.7 (**a**) Agropasturesilvofishery system with (**b**) alley cropping

Fig. 16.8 Two types of apiculture system by Yoan farm in Kalampangan village

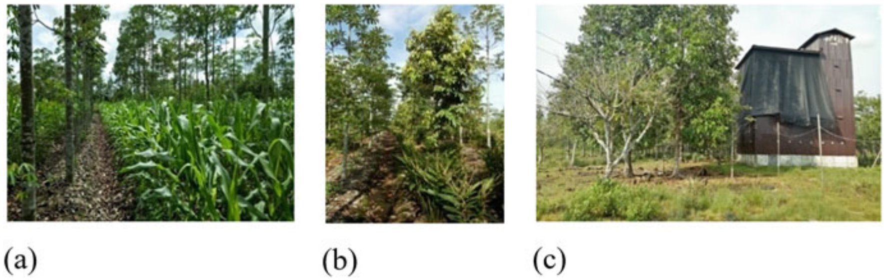

Fig. 16.9 The agrosilvopastoral system in backswamp physiography. (**a**–**b**) Mixed vegetation. (**c**) A house for swallow bird on the farm

agrosilvopastures developed by local farmers: (a) *D. polyphylla* is planted with a spacing of 5 × 5 m; between two lines of *D. polyphylla*, annual crops are planted. Fodder grass is planted on the edge of the land. Farmers raise cattle (cows and goats). (b) Jelutong species are planted mixed with seasonal plants. In the middle of the

Table 16.4 Characteristics of the agrosilvofishery system in peat dome in the Kalampangan village

S. no	Agroforestry system	Planting patterns and land arrangement	Composition of components
1.	Agrosilvofishery	Perennials are planted on the edge of the land. In the middle, a dug pond is made for fish farming. Vegetables are planted on the edge of the fish pond. Fish pond size: 2–3 m wide, 10–15 m long, 1.5–2 m deep.	Wood crops: Breadfruit, gaharu, matoa, lamtoro, hybrid coconut. Vegetable crops: Kaylan, mustard greens, pulled spinach, kale, chilies, lettuce, green onions. Types of fish: Catfish, gabus, papuyu and karper.
		Perennials are planted on the edge of the land. In the middle, a tarp pond is made for fish farming. Vegetables are planted on the edge of the fish pond. Fish pond size: 4 m wide, 10 m long, 1.5 m deep.	Wood crops: Agarwood, hybrid coconut. Fruit crops: Rambutan, soursop. Type of fish: Catfish.

land, a house for swallow birds is built. Swallow's manure can be used for biological fertilizers.

16.3.1.3 Agroforestry in the Peat Dome

The five agroforestry systems in the peat dome of Kalampangan village are agrosilviculture, agrosilvopastoral, silvopastoral, apiculture and agrosilvofishery. The area of land used for agricultural cultivation with agroforestry systems is about 0.5–2 ha. The agroforestry characteristics are summarized in Tables 16.3 and 16.4.

Agroforestry, where Woody Trees Are Cultivated with Vegetable Crops

D. polyphylla are overlaid with vegetable crops. The cropping patterns and land arrangement in this system can be grouped into three groups. (1) Seasonal plants are planted in an alley formed by two rows of *D. polyphylla*. On the inside, a "parit cacing" (small ditch) is made, which divides the land into plots of plant locations. The constituent components consist of (a) *D. polyphylla, A. malaccensis* (woody trees); (b) fruit crops: durian, rambutan, papaya, soursop, orange, pineapple; (c) seasonal crops: corn, cassava, chili, eggplant, mustard greens; (d) shade plants: *Ceiba pentandra*. (2) The land is divided into two blocks. The first block is for seasonal crop cultivation. The second block is for tree cultivation or is allowed to become forest from natural regeneration. Woody trees, like *C. rotundatus* and *D. polyphylla*, are planted with seasonal crops and fruit trees. (3) Woody trees (jelutong and aloe wood) are planted around the agricultural cultivation area (Fig. 16.10).

Fig. 16.10 Agrisilvicultural systems in the peat dome. (**a**) Line tree planting with vegetable crops. (**b**) Tree and vegetable crops are in a separate block. (**c**) Fruit trees and timber trees

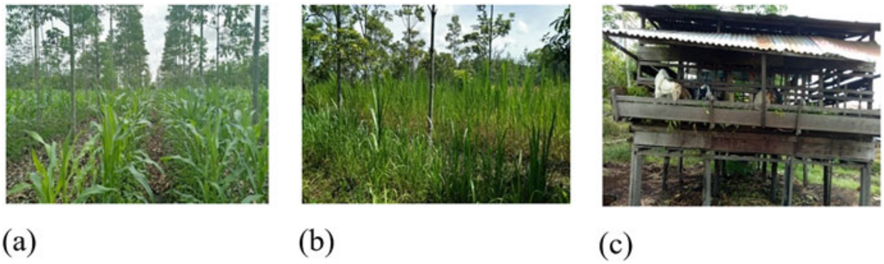

Fig. 16.11 Agrosilvopasture system in peat dome. (**a**) Trees and seasonal crops. (**b**) Trees and fodder grass. (**c**) Cattle shed

Agrosilvopastoral

In this system, the land is used to cultivate vegetables, *D. polyphylla* trees and forage. Swamp Jelutung planted with a spacing of 5 × 5 m. Annual crops are planted in between two jelutong lines. On the edge of the land is planted with fodder grass. Fruit and tuber crops, such as taro, cassava and rambutan, are also planted. In addition, farmers raise livestock of cows and goats (Fig. 16.11).

Silvopasture

In this system, *D. polyphylla* trees are used for duck farming and goat grazing. The advantage of this model is that the *D. polyphylla* stands free from weeds and gets fertilizer from manure while they create a good environment for swallow. Swallow's droppings can be used as organic fertilizer (ameliorant) after fermentation. The constituent components consist of tree species (such as *D. polyphylla* and *A. malaccensis*), fruit plants (rambutan and pineapple), seasonal crops (such as corn, cassava, chilies, eggplant, mustard greens), and livestock, such as chicken, ducks, swallows, cows, and goats (Fig. 16.12).

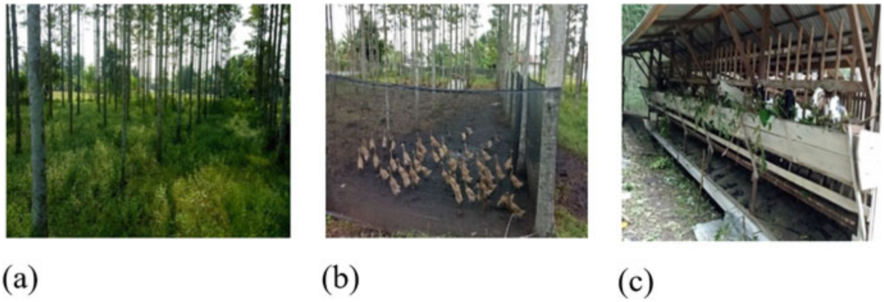

Fig. 16.12 Silvopastoral system in the peat dome. (**a**) Weeds on the farm (without ducks), (**b**) the farm with ducks, no weeds, (**c**) goats in a cage

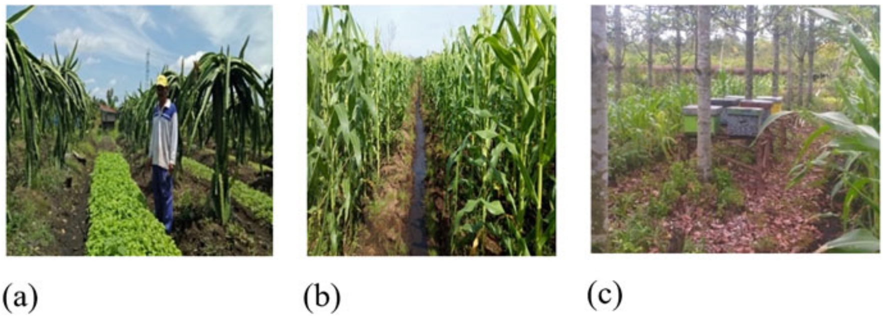

Fig. 16.13 Crops as source of nectar and pollen for honey bees. (**a**) dragon fruit, (**b**) corn, (**c**) colony box of *A. mellifera*

Apiculture

Honey bee (*Apis mellifera*) colony boxes (hive) are placed in the yard, where a number of bee food sources were planted as a source of pollen and nectar, for example, ornamental plants, corn, spinach, dragon fruit (Fig. 16.13).

Agrosilvofishery

In this system, the land is used for vegetable cultivation, tree crops, and fish cultivation (Fig. 16.14). Pond wastewater can be used as liquid organic fertilizer, while agricultural waste can be used for fish feed. Based on the cropping pattern and land arrangement, this system can be grouped into two groups. (1) Woody plants (such as breadfruit, aloe wood, *Pometia pinnata, Leucaena leucocephala*, and hybrid coconut) are planted on the edge of the land. In the middle is a fish pond in size of 2–3 m wide, 10–15 m long, 1.5–2 m deep. Vegetables are planted on the edge of the fish pond (such as papuyu, lais, karper). (2) Perennials (such as agarwood, hybrid coconut, rambutan, and soursop) are planted on the edge of the land. A plastic pond is made for catfish farming in the middle, in size of 4 m wide, 10 m long, 1.5 m

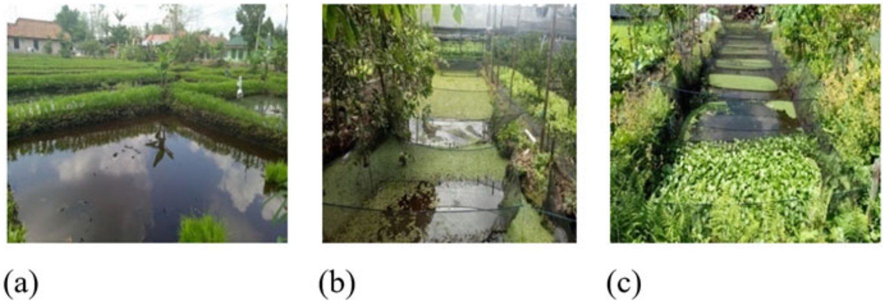

Fig. 16.14 Agrosilvofishery system in peat dome. (**a**) Fish pond, (**b**) plastic fish pond, (**c**) vegetable cultivation

deep. Vegetables are planted on the edge of the fish pond. Table 16.4 describes the agrosilvofishery system in the physiography of the peat dome.

16.3.1.4 Agroforestry System to Rehabilitate Degraded Peatland

Based on the agroforestry system that local farmers have developed, efforts to rehabilitate degraded peatlands can be carried out using the following techniques: (1) agroforestry, (2) silvofishery, (3) silvopastoral, (4) agrosilvopastoral (combination of annual crops, woody tree, and livestock), and (5) agrosilvofishery (combination of fish-tree-annual crops). Its application depends on the dominant resources available at the development site. The most common tree species cultivated in agroforestry systems is *D. polyphylla*. Swamp jelutung grows on the lowland (<100 m asl), plain landforms, shallow groundwater, and permanently or seasonally submerged land. It can be planted in combination with various trees and annual crops that have been described above (Sects. 16.3.1.2 and 16.3.1.3).

16.4 Integrated Agricultural Model (IAM) for PHU Management

The integrated agricultural model based on the agroforestry landscape that local farmers have developed in the Kalampangan village area has specific characteristics. This model can be used as a basis for further improvements and implemented in the similar characteristic condition in PHU Kahayan–Sebangau river.

16.4.1 Cultivation Practices on Shallow Peat

Important aspects of crop cultivation with agroforestry systems on shallow peatlands (peat thickness 50–100 cm) include land preparation, soil fertility management, water management, and type of mixed cropping. The following description explains this important aspect.

16.4.1.1 Land Preparation

This activity is carried out before planting, which includes cutting down weeds and ploughing the soil. The equipment used in this activity is the machete, hoe, and "sundak." Local farmers in land preparation use machete for cutting down weeds and use as minimum tillage. Land preparation with minimal tillage is to minimize soil destruction so that the pyrite layer will not be exposed. The land preparation technique carried out by local farmers can be divided into two, namely, mounding (tongkongan) and "surjan" (Fig. 16.15). For farmers with large capital, the "surjan" technique was created. On the other hand, the use of the mounding (tongkongan) technique is mostly done by farmers who have small capital and then replace it with the "surjan" technique when conditions allow. Usually, "surjan" technique was applied in developing agroforestry systems on thin peatlands to minimize the tidal effect and optimize the land use. In the "surjan" technique, the land is divided into 80% of sunken beds (locally known as "tabukan"), which is the lower part of the land, and 20% of the raised beds or mounding, which is the higher part of the land. "Tabukan" is usually planted with rice or saturation-resistant plants, while the mounds are planted with rubber, jelutong, secondary crops, fruit crops, and/or forage.

16.4.1.2 Management of Soil Fertility

This activity concerns ways to increase fertility and efforts to conserve land productivity. The source of nutrients for plants is obtained by processing the rice straw and weeds by means of scattering. This technique is a form of local wisdom of local farmers in obtaining nutrient sources for cultivated plants. This is done by twisting (rolling) the straw and weeds resulting from weeding at one of the stages of land preparation activities in rice cultivation. Spinning is done after the weeds wither, namely, by collecting weeds into one roll in the form of small mounds. The process of making organic fertilizers with the scatter ball system is as follows: (1) cleaning or weeding the weeds using a ploughing tool, (2) weeds that have been cut are left for 2–3 days to wilt, (3) spinning is carried out on weeds that have wilted, (4) evenly spreading the crushed (weathered) material (Maftu'ah et al. 2013).

Another wisdom practiced by local farmers in managing land fertility in rice cultivation is how to transfer seeds three times, which are called "taradak," trace, and

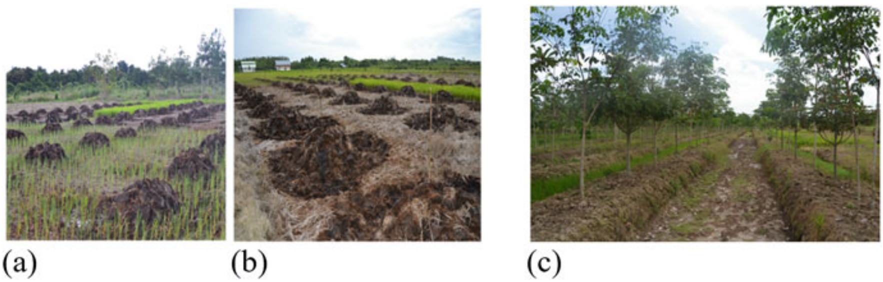

Fig. 16.15 (**a**–**b**) Preparation of mound engineering (**c**) "surjan" technique

"ampak." In addition to maintaining soil fertility, this method is also an effort to anticipate a lack of labor. Rice straw and weeds are used as organic materials to store nutrients that will be released slowly into groundwater and used by plants as a slow-release fertilizer. Also, the organic matter produced by the scattered ball in and above the soil surface protects and helps regulate soil temperature and humidity. This practice is often combined with other techniques with complementary functions, for example, soil cultivation and water collection with canal blocking ("tabat" system).

Farmers' wisdom in utilising debris and weeds as organic material is specific for each individual farmer. In general, these can be grouped into four groups: (1) applying it directly to the soil, either as mulch on the soil surface or buried in the soil; (2) burning organic material (resulting in mineralization) and the ashes from the combustion function as a fast and inexpensive ameliorant; (3) composting organic material using scatter ball technique; and (4) making it as animal feed, then livestock manure can be used as manure.

16.4.1.3 Water Management

This activity is carried out by local farmers, which includes the construction of a canal and a canal blocking (tabat) system. Local farmers implement the canal blocking system to maintain water level during the planting season around March–April. "Tabat" is opened at the end of the dry season or before the rainy season to remove heavy metals in the soil (such as Al, Fe, H_2S). Water systems that have been tested well in tidal areas are the one-way flow system and the block system, or called dam overflow.

16.4.1.4 Crops Planting System

Agroforestry systems on peatlands that local farmers have developed can serve as a basis for further development. The cropping patterns that local farmers have developed can be grouped into three groups: (1) agrosilvofishery, (2) mixed cropping, and (3) alley cropping. Table 16.5 describes the crops planting system.

16.4.2 Cultivation Practices on Moderate Thick Peatland

Important aspects of agricultural cultivation with agroforestry systems on thick peatlands (peat thickness around 200–300 cm) include land preparation, planting, soil fertility management, water management, and cropping patterns. The descriptions of the five important aspects are as follows.

16.4.2.1 Land Preparation

This is the most important aspect in the cultivation of agroforestry systems on thick peatlands. The land preparation is carried out by dividing the land into plots with trenches as a barrier between the plots (split-plot technique). The trenching has a dual function, namely, a water management system and a firebreak, especially for underground fires. The existence of a trench can maintain the groundwater level (soil

Table 16.5 Agroforestry system that has developed on shallow peatlands

Agroforestry	Brief description	Main component
Alley cropping with mounding technique	Wood trees are planted in mounding soils, while paddy rice is planted in the lower soil surface.	Trees: Rubber and jelutung Annual crops: Paddy rice
Alley cropping With "surjan" technique	The land is divided into lower part (tabukan), which is planted with local rice (annual rice), and the mounding part, which is planted with perennials and woody trees (rubber and/or jelutong).	Trees: Rubber and jelutung. Annual crops: Paddy rice
Agrosilvofishery With "surjan" technique	The land is divided into lower part (tabukan), which is used as a fish pond or *beje* (fish trap pond) and a part of the mounds planted with woody trees (jelutung, durian, agarwood, rubber, and *M. odorata*), and fruit trees (snake fruit).	Plants: Jelutung, durian, agarwood, rubber, and *M. odorata*, and fruit trees (snake fruit).

(a) (b)

Fig. 16.16 (**a**) Pineapples are planted along a ditch, (**b**) cassava plants to accelerate decomposition of peat and soil compaction

moisture) between 30 and 40 cm from the soil surface so that it provides an opportunity for plant roots to grow well (soil drainage and aeration are good). The trench size used for 1 ha of land is 30–40 cm for the width and depth of the trench.

Pineapples are planted around the ditches to compact the soil around the trench so that it is not prone to landslides, as a green firebreak especially for surface fires, and to prevent weed growth on the cultivated land. According to Noor (2001), the constraints of planting trees on peatlands are the low soil bulk density and the small carrying capacity of the soil so that plants fall easily with increasing plant weight on the ground. Increasing the carrying capacity of the soil requires compaction, especially in the root zone or plant pathways. In general, the compaction techniques employed by local farmers can be grouped into two groups: using vegetation and compaction carried out in the planting hole. The vegetation that is commonly used for soil compaction activities is pineapple and cassava (Fig. 16.16). However, some farmers do not use pineapples for soil compaction because the roots

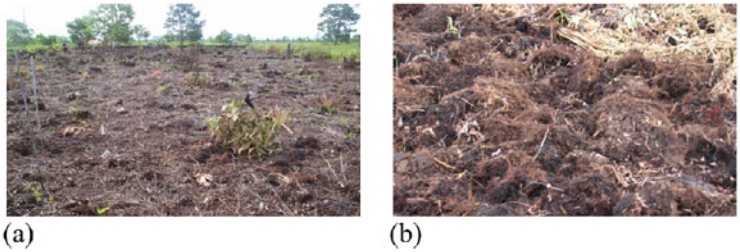

Fig. 16.17 (**a–b**) Cleaning the roots of the ferns

of pineapples are difficult to rot. Cassava has high acidity resistance, and it accelerates the decomposition of the organic materials (Muslihat 2003).

When preparing the land, especially for peatlands that are used for agricultural cultivation for the first time, it is necessary to clean the roots of ferns (*Stenochlaena palustris* and others) (Fig. 16.17). For smallholder farmers, this is usually done manually by using machete and hoe.

16.4.2.2 Planting

Two things that need to be considered in planting seedlings on peatlands are the making of planting holes and the condition of the seeds that are ready for planting. The steps for making planting holes commonly practiced in the field are as follows: (1) the location of the planting hole is cleared of vegetation growing on it; (2) remove fern roots at the planting point so that the seedling roots are in direct contact with the peat layer and chop the peat so that it becomes compact and no air cavity; (3) making a planting hole the size of the polybag; (4) tear the polybags only on the lower surface without removing them from the seedlings, with the aim that the soil moisture of the seed media does not break when there is fluctuation because it has not yet merged with the peat in the field; (5) inserting the polybag into the planting hole that has been made with the top end of the polybag parallel to the soil surface and the bottom of the polybag touching the peat layer instead of the fern roots; (6) compacting the peat around the polybags that have been planted to blend with the soil in the field. Seedlings that are ready to be planted in the field are those whose stems have undergone a hardening process, and the shoots are in a dormant state (resting), which forms as bud, not as a young leaf. This is important because seedlings that are still in young leaf buds will tend to wither when planted in the field quickly. This wilting condition often continues until the death of the seedlings in the field. The height of the seeds to be planted must be higher than the puddle (during the highest inundation) so that the seeds do not sink.

16.4.2.3 Management of Soil Fertility

The provision of ameliorant is important to improve soil condition. Some ameliorants commonly used by local farmers are lime, mineral soil, and ash from burning grass and litter. After harvesting agricultural crops, local farmers will do a

(a) (b)

Fig. 16.18 (**a**) The process of managing soil fertility by making "baluran." (**b**) Ameliorant application in each planting hole

(a) (b)

Fig. 16.19 (**a**, **b**) Small ditch (parit cacing) profile for water management

fallow period to give a resting time for their land. In the subsequent land preparation, the grass is sprayed with herbicides. Ameliorant is given in the planting hole (Fig. 16.18).

16.4.2.4 Water Management

Soil moisture regulation is made by making small ditch surrounding the land. The size of the outer drainage ditch (circumference) of the land is 30–40 cm in width and depth, while the inner ditch measures 15–30 cm for its width and depth (Fig. 16.19).

In addition to drainage ditches, farmers also make some rectangular wells ($1 \times 1 \times 2$ m^3) as a source for watering the plants (Fig. 16.20). Farmers with large capital are also developing artesian well as a water source in the dry season. Table 16.6 describes agroforestry patterns developed on thick or deep peatlands.

The development of sustainable agricultural cultivation on peatlands with an agroforestry system is prioritized on peatlands that have been converted but are not suitable for agricultural and plantation crops. The chosen agroforestry system (agroforestry, agrosilvofishery, agrosilvopasture, silvopasture) depends on dominant

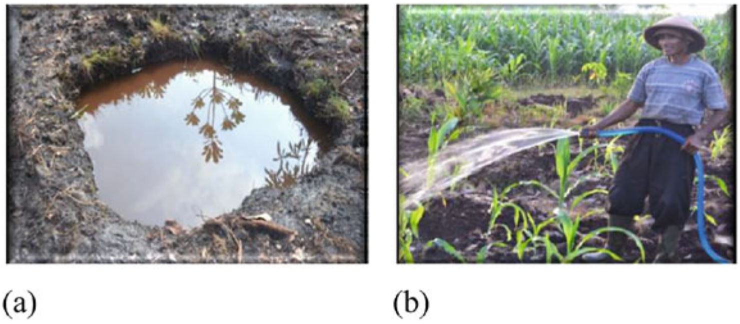

Fig. 16.20 (**a**) Well profile. (**b**) Watering from pump wells as a source of water in the dry season

Table 16.6 Agroforestry patterns that have developed on thick/deep peatlands

Agroforestry	Short description	Main component
Mixed cropping With technique Swathed tile	The cultivated land is surrounded by a drainage ditch 30–40 cm in width and depth. The plants planted were rambutan and jelutung marsh, which were planted alternately per lane.	Trees: Jelutong and rambutan. Annual crops: Pineapple
Alley cropping With technique Swathed tile	The land is divided into plots bordered by small trenches (parit cacing). Plots with a wider area are narrower for planting trees, while those with a wider area are for growing food crops.	Trees: Marsh jelutong. Annual crops: Vegetables (corn, mustard greens, string beans, green onions, etc.).
Agrosilvofishery	A dug pond measuring 1–2 m wide and 5–10 m long. Around the pond is planted with seasonal plants (spinach, kale, mustard greens, etc.). At the boundaries of the land are planted agarwood, *L. leucocephala*, and fruit trees (guava, rambutan).	Trees: *Aquilaria malaccensis*, guava, rambutan. Seasonal crops: Spinach, kale, mustard greens. Fish: Catfish, cork, papuyu
Silvopasture	Model 1: Under the jelutong stand, the cultivation of forage plants (elephant grass) is cultivated. Model 2: Duck cultivation is carried out under the jelutong stand.	Tree: Jelutong. Annual crops: Animal feed. Livestock: Ducks

resources available at the development site. Sustainable agroforestry on peatlands is intended to diversify commodities, businesses, and farmers' income. Hence, it must go through a diagnostic activity to see the needs of local farmers and design an agroforestry model through the active participation of the local farmers.

16.4.3 Development of Zero Burning and Zero Waste Agriculture on Peatlands

16.4.3.1 Ameliorant as Ash Substitute

Forest and land fires are major threats to the sustainability of agriculture and peat ecosystems. Burning peatlands is considered dangerous because it can trigger forest and peatland fires. Peatland fires will be difficult to distinguish if they are underground fires that are not visible from above but can spread to nearby places (Najiyati et al. 2005). The control burning on peatland affected productivity.

To reduce fire occurrence on forest and land is to practice cultivation without burning and without waste. Currently, local farmers are still using control burning in land preparation, locally known as “besik-bakar” (Fig. 16.21).This aims to clear the land and to obtain ash as an ameliorant material. Amelioration is used to improve soil fertility.

The problems as the result of control burning are burned peat surface and subsidence (Fig. 16.22). The thickness of the peat that is carried out by the controlled burning ranges from 1.0 to 8.5 cm (Table 16.7). The decline of peatland surface due to control burning is 4.3 cm. If the land is planted three times a year, the peatland

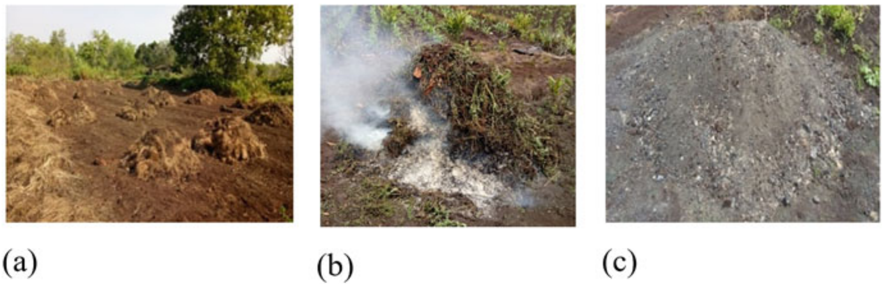

Fig. 16.21 The practice of control burning (besik-bakar). (**a**) A pile of dry grass. (**b**) Burning the pile of grass. (**c**) The ashes

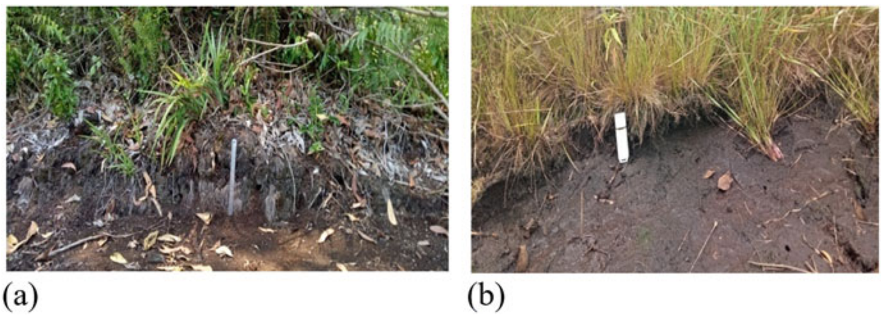

Fig. 16.22 (**a**, **b**) Surface subsidence of peat due to control burning (besik bakar) practice

Table 16.7 Thickness of peat brought on by "besik-bakar" activity

Plot name	Burnt peat thickness (cm)	Standard deviation
TIY	1.0	0.60
PAI	1.2	0.86
SLA	1.6	0.99
SAU	1.8	1.03
SUI	2.1	0.49
SAM	3.2	0.41
SUN	3.7	0.51
SUT	3.7	1.50
TRI	4.5	0.54
SUP	5.7	0.36
SK	6.3	0.64
SUR	7.0	0.41
TUG	7.3	0.48
SUM	7.7	0.47
TUK	8.5	1.96

surface will decrease by 12.9 cm per year. The continued decline of peatlands causes flooding in the rainy season and even become permanent swamps.

The choice of ameliorant considers the land classification and the evaluation results of land suitability on selected plant commodities (Basu et al. 2011; Hartatik 2012). Amelioration can be done by adding organic, inorganic, or a combination of both. Organic ameliorant materials include manure, compost, straw, and agricultural debris. Inorganic ameliorant materials are lime or dolomite, zeolite, volcanic ash, and river mud (Salampak 1999; Ervina et al. 2016). Peat ameliorant is a material used to increase the fertility of peatland, which will be used for crop cultivation activities through improving physical and chemical conditions. The criteria for a good ameliorant for peatlands have high base saturation (BS), increase pH significantly, improve soil structure, having complete nutrient content, and neutralizing toxic compounds (acids organic). Ameliorants can be in the form of organic, inorganic, or a mixture of both (Salsi 2011; Maftu'ah et al. 2013; Masganti et al. 2014). Ameliorant used by farmers to improve peatland fertility in PHU Kahayan–Sebangau in the Kalampangan village (Table 16.8).

It is known that the ameliorant material used by local farmers is proven to increase soil pH and soil alkalis (Table 16.8). The ameliorant material traditionally used by local farmers has met the requirements for good ameliorant, which has high alkaline base saturation (BS), is able to reduce the acidity of peatlands (increases pH significantly), and has complete nutrient content. The laboratory analysis of ameliorant nutrient content in the four study locations as listed in Table 16.11 shows that the ameliorant used by local farmers can be used to improve the peatland fertility. The ameliorant can increase the pH and contain nutrients according to the national standard (*Standar Nasional Indonesia*, SNI) of compost. This is very necessary considering that peatlands contain a low number of macro and

Table 16.8 Chemical properties of some ameliorants used by farmers in the PHU Kahayan–Sebangau river, Kalampangan village

Chemical properties	Mixed ameliorant				National standard
	ash +chicken manure	ash+dolomite +chicken manure	ash +goat manure	ash+dolomite +paddystraw +cow manure	
pH H_2O	6.74	7.2	7.8	5.99	6.8–7.49
C org (%)	19.36	27.66	18.56	18.85	9.8–32
N_{total} (5)	19.36	27.66	18.56	18.85	0.4 (min)
$P_{available}$ (ppm)	0.55	5.11	192.04	295.63	0.1 (min)
K (me/100 ga)	0.64	0.12	0.4	0.37	0.2 (min)
Na (me/100 g)	0.12	0.02	0.03	0.42	–
Ca (me/100 g)	14.63	5.37	4.66	9.16	25.5 (max)
Mg (me/100 g)	12.28	7.96	4.12	2.7	0.6 (max)
Cation exchange capacity	34.5	29.84	28.16	49.5	–
Base saturation	80.21	45.38	32.67	25.56	–

micronutrients (Najiyati et al. 2005). The ameliorant material study provides optimal results. Chicken manure is a source of P and K elements, ash due to burning organic matter as an N binding, and as a source of P elements, lime, or dolomite as a source of Ca and Mg elements.

The content of ameliorant elements can be further explained as follows—first, the degree of acidity or pH (potential of hydrogen). One good indicator of ameliorants is to have a pH close to neutral. The ameliorant pH value commonly used by local farmers ranges from 5.99–7.8. Based on these results, the ameliorant commonly used by the farmers has met the requirements of a good ameliorant. The four ameliorants are categorized as slightly acidic- neutral.

Second, the element content of C, N, and C/N. Nitrogen is a key element in amino acids and nucleic acids. Therefore, nitrogen is essential for all life. Ameliorant N content commonly used by farmers ranges from 18.56–27.66%. The content of the N ameliorant element has met the SNI requirements. The C and N content of the four ameliorants is in the very high category (>0.75) (Harjowigeno 1996). The C/N ratio of ameliorant is 1. This means it is in a low category. The C/N ratio is an important parameter to determine the quality of ameliorants. This ratio is used to determine whether ameliorants are "ripe" enough or not (Wahyuningtyas et al. 2010).

Third, the element content of mineral cations (K, P, and Mg). Ameliorant content ranged from 0.55–295.63%. The elemental content of ameliorant ranges from 0.12% to 0.64%. Samekto (2006) states that good ameliorants contain macronutrients $N > 1.5\%$, P_2O_5 (phosphate) $> 1\%$ and K_2O (potassium) $> 1.5\%$. Based on the criteria in Table 16.9, the P elements contained in type 1 and type 2 ameliorants are in the very high category (> 60). Meanwhile, the ameliorant of type 3 and type 4 is very low (<10). The ameliorant used by local farmers has a very low K content (<10). Ameliorant type 3 and type 2 contain very low elemental Na (<0.1).

Table 16.9 The chemical properties of ameliorants used by farmers in Kalampangan village

S. no.	Ameliorants	Chemical properties of ameliorants							
		pH H_2O	C Org (%)	N total (%)	P_{avail} (ppm)	K (me/100 g)	Na	Ca	Mg
1.	AK.01	6.58	9.20	9.20	4.60	1.85	0.75	1.22	7.62
2.	AK.02	6.74	19.36	19.36	0.55	0.64	0.12	14.63	12.28
3.	AK.03	7.80	18.56	18.56	192.04	0.40	0.03	4.66	4.12
4.	AK.04	5.99	18.85	18.85	295.63	0.37	0.42	9.16	2.71
5.	AK.05	7.89	19.72	19.72	474.93	1.56	0.01	2.31	4.44
6.	AK.06	7.29	10.29	10.29	282.76	1.26	0.01	1.81	3.51
7.	AK.07	7.76	29.53	29.53	433.28	0.16	0.02	5.88	8.23
8.	AK.08	7.20	27.66	27.66	5.12	0.20	0.02	5.37	7.96
9.	AK.09	7.67	6.49	6.49	392.35	0.19	0.03	1.17	3.20
10.	AK.10	7.68	4.76	4.76	495.98	0.13	0.19	1.94	0.94
11.	AK.11	6.96	18.42	1.12	627.38	53.57	18.37	35.51	29.90

Information: AK.01 = ash + dolomite; AK.02 = ash + chicken manure (1); AK.03 = ash + goat dung; AK.04 = goat manure + duck manure + straw compost; AK. 05 = ash + chicken manure + cow dung; AK.06 = ash + sand + chicken manure; AK.07 = ash + chicken manure (2); AK.08 = ash + chicken manure + petroganic; AK.09 = ash + sand + chicken manure + goat manure; AK.10 = mineral soil + goat manure + chicken manure; AK.11 = water hyacinth compost + cow dung

Ameliorant type 4 contains a moderate amount of Na element (0.4–07). Meanwhile, type 1 ameliorant contains low category Na elements (0.1–0.3). Ameliorant type 2 and type 3 contain elements of Ca, including the low category (2–5). Ameliorant type 1 has a high content of the element Ca (11–20). Ameliorant type 3 contains a moderate amount of Ca element (6–10). Ameliorant type 1 has a very high category of Mg content (> 8). Ameliorant type 3, type 2, and type 4 contain high-category Mg elements (2,1–8). Ameliorants of type 4 have a very high CEC (> 40). Meanwhile, ameliorants of type 2, type 3, and type 1 have high CEC categories (25–40).

The results of the identification of ameliorant materials used by farmers in KHG Kahayan–Sebangau, Kalampangan Urban Village, show that there are 11 kinds of ameliorant composition used (Table 16.9).

Also, there are 12 single ingredients used as ameliorants (Table 16.10). The single material used as an ameliorant is derived from manure and compost from organic matter decomposition. It is known that in the PHU Kahayan–Sebangau–Kalampangan village area, there are 12 raw ameliorant materials. This potential can be used to support agriculture without burning on peatlands. Farmers can mix their ameliorants according to the needs of the plants to be planted. For example, if you want to cultivate root crops such as taro, cassava, sweet potatoes, ameliorants made from wallet dung containing high P elements.

The peatland that is used for plant cultivation has better chemical properties than peatland that is not used for plant cultivation (Table 16.11), as they often receive ameliorant and fertilizer input during the plant cultivation process.

Table 16.10 Chemical properties of single ameliorant substance

S. no.	Amelio-rants	Chemical properties of single ameliorant									
		pH H_2O	C Org (%)	N (%)	P (ppm)	K	Na	Ca	Mg	CEC	SB
						(me/100 g)					
1.	AT.01	7.6	38.2	38.2	1269.7	0.1	0.02	2.7	2.0	51.4	9.3
2.	AT.02	7.1	27.2	0.6	714.5	1.3	4.1	0.6	3.1	85.7	10.6
3.	AT.03	6.9	48.0	1.9	423.2	6.8	2.3	3.8	3.3	129.1	12.6
4.	AT.04	5.7	43.7	43.7	284.6	0.1	0.8	2.3	1.4	79.6	5.8
5.	AT.05	7.7	35.6	1.2	142.5	2.6	4.2	57.7	2.9	76.6	88.0
6.	AT.06	6.9	30.6	30.6	Tu	0.1	0.04	2.9	2.3	39.7	13.6
7.	AT.07	7.3	22.0	22.0	Tu	0.2	0.04	1.3	3.6	17.6	29.2
8.	AT.08	7.9	16.8	0.5	15.7	2.3	0.1	15.9	8.0	29.3	90.0
9.	AT.09	6.4	13.3	0.5	4.5	1.0	0.2	2.2	7.5	43.4	25.0
10.	AT.10	7.6	15.3	0.5	2.2	2.5	1.4	23.2	1.7	41.5	70.0
11.	AT.11	8.2	4.0	0.7	11.8	0.2	0.03	9.5	1.3	15.7	70.2
12.	AT.12	6.6	34.1	2.7	1857.8	83.8	18.1	74.3	54.4	114.3	201.7

Information: AT.01 = chicken manure (1); AT.02 = quail dung; AT.03 = goat dung; AT.04 = swallow droppings; AT.05 = cow dung; AT.06 = ash (1); AT.07 = Abu (2); AT.08 = Abu (3); AT.09 = ash (4); AT.10 = ash (5), AT.11 = fertile soil (topsoil); AT.12 = water hyacinth compost; Tu = not quantifiable; CEC: cation exchange capacity; SB: base saturation

Table 16.11 Ameliorant amendment effect on soil chemical properties at different peatland uses

Chemical properties	Horticulture		Agroforestry		Fallow		Shrubs	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
pH H_2O	4.0	0.3	3.5	0.3	3.2	0.2	2.9	0.1
C org (%)	43.8	9.0	44.7	12.3	50.1	2.2	51.1	2.6
N total (%)	19.1	25.9	4.3	4.5	24.6	33.8	25.1	34.2
P available (ppm)	369.8	515.4	124.2	157.3	277.4	22.0	30.1	14.5
K (me/100 g)	1.2	1.4	0.8	0.2	0.3	0.1	0.3	0.1
Na (me/100 g)	0.6	0.8	0.7	0.7	0.1	0.1	0.6	0.6
Ca (me/100 g)	9.3	2.5	9.2	11.0	10.2	3.2	4.0	0.7
Mg (me/100 g)	5.6	3.8	7.5	0.01	3.9	0.7	2.6	0.3
Cation exchange capacity	154.5	16.6	125.0	3.1	162.6	12.0	212.5	6.5
Base saturation	10.7	1.1	14.5	8.9	9.0	1.6	3.5	0.7

16.4.3.2 Zero Burning on Land Preparation

The technique of preparing land without burning or zero burning is a method of clearing land by processing weeds and organic materials, which are usually burned, into economic value items in the form of compost blocks, seed media, feed pellets of livestock and fish, and energy pellets (wood pellets). Some weed species, such as *Plantago major* (sasendok or uyah-uyahan), *Dianella ensifolia* (delingu), *Asplenum nidus* (fern), *Baccaurea bracteata* (asem-aseman), *Cratoxylum glaucum* (Geronggang), *Stenochlaena palustris* (Kelakai), *Clerodindrum* sp. (lombok-lombokan), and *Melastoma malabathrichum* (karamunting), are available in abundance on peatlands. According to Nurjannah (2006), weed species contain protein and minerals that can meet livestock needs. *Plantago major* contains protein (9.1%), calcium (2.9%), phosphor (0.2%), magnesium (0.8%), and zinc (13.0%), while *Stenochlaena palustris* (kelakai ferns) contains protein (11.0%), calcium (1.1%), phosphor (0.1%), magnesium (1.1%), and zinc (11.1%).

Moreover, weeds can be processed into planting media and compost block. Compost block is used to support the successful rehabilitation and reclamation of ex-mining plants. Processing of weeds into products, such as feed pellets of livestock and fish, energy pellets, planting media and block compost, is economically beneficial for the communities (Fig. 16.23). It is also a preventive action on forest and land fires. By processing the weeds into energy pellet, farmers may provide energy for domestic uses. The combination of energy pellets and biomass compost can build energy independence for villagers. Farmers are also able to feed their livestock and fish independently. It is hoped that the application of planting media to agriculture on peatlands can increase the capability of farmers in meeting fertilizer needs independently.

Fig. 16.23 Processing of weeds into beneficial products. (**a**–**b**) Feed pellet processing. (**c**) Energy pellet from weeds can be used for cooking. (**d**) Organic materials to be used as compost block

16.5 Conclusion

Rehabilitation of degraded peatlands can be carried out using the following techniques: agroforestry (agrosilvic structure), silvofishery, silvopastoral, agrosilvopastoral (annual-tree-livestock crops), agrosilvofishery (fish-tree-annual crops), and apiculture (beekeeping). Its application depends on the dominant resources available at the development site. Ameliorant material in the four peatland typologies studied can increase soil pH and soil alkalis. The ameliorant material traditionally used by local farmers has met the requirements of good ameliorant, which has high base saturation (BS), is able to reduce the acidity of peatlands (increases pH significantly), and has complete nutrient contents. These can be adopted and applied in other places which have almost the same characteristics (similar). The development of the agroforestry system is carried out through a diagnostic activity to see the needs of local farmers and designed to model the cropping through active participation so that local farmers can practice it.

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SmarteR Approach for the Mapping of Invasive Plant Species

17

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Abstract

Invasive species distribution has caught global attention due to its detrimental effects on biodiversity. Species that have become invasive often come from climatic conditions similar to those found in other parts of the world. Species distribution modelling (SDM), also referred to as habitat suitability mapping, ecological niche modelling, or climate envelope modelling can be used to map potential sites of invasion probability. Some of the major SDM techniques that fall under this category are the Bioclim model, Domain model, and Maxent model. A more sophisticated set of R tools has made it simpler to estimate a species' habitat range based on its geolocation. For SDMs to be successful, it must be possible to accurately describe the distribution of the species in question. Based on climate data and other environmental criteria such as elevation, surface water, soil moisture, and land use as well as other human-induced variables, SDMs attempt to map anticipated species distributions or habitat suitability. We describe here two major approaches of classical SDM and machine learning techniques for mapping invasion. Machine learning comprises algorithms that do not rely on rule-based programming; instead, it learns from the data. It is increasingly being used to build predictive habitat suitability maps using binary response data and environmental predictors. Various models that utilize machine learning include Generalized linear model (GLM), Support vector machines

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(SVM), Gradient boosting machine (GBM), k-nearest neighbor (kNN), and Random Forest (RF). This chapter will discuss various modelling techniques with practical examples along with model evaluation using R language and platform.

Keywords

Species distribution modelling · Machine learning · R language · Maxent · Random forest · kNN · Support vector machine · bioclim

17.1 Introduction to Species Distribution Modelling

Invasive plant species are those that have been brought to a new location and are not native to the region. They negatively impact the wild ecosystems and agriculture (Early et al. 2016). They compromise the stability of the ecosystem by altering the dynamics of plant communities and by competing with the local flora. This affects the nutrient cycle, increases the soil acidity, and inhibits their regeneration (Tiedeken and Stout 2015). The invasive plants incline to change their niche more quickly than the native species, and they are more prone to adapt to the new environment (Liu et al. 2017; Shrestha and Shrestha 2019). Around 6500 invasive plant species are found globally in terrestrial and aquatic habitats, and one-sixth of all land area is vulnerable to invasion (Early et al. 2016). There is a pressing need to learn more about how invasive species spread and what impact they have now and in the future (Bertelsmeier et al. 2013). As a result, biological invasions and their consequences for ecosystems and global economy have become academic topics of interest (Richardson and Pyšek 2008; Vilà et al. 2011).

SDM is an extremely useful method for modelling species spatial distributions, analyzing organisms' possible response to climate change, defining species niches using environmental factors, and supporting ecological management (Guillera-Arroita et al. 2015). However, a proper framework for modelling invasive species that often demonstrate rapid transformations is yet to be developed for non-invasive species. Therefore, the way forward includes further efforts to explore and develop models that provide relevant insights on invasive species distribution and habitat.

The basic premise of SDMs is to map predicted species distribution or habitat suitability, using georeferenced species presence data and environmental parameters, including elevation, temperature, rainfall, and land use, and additional factors such as population, distance from roads, etc. The final output would be a habitat suitability map on a zero-to-one scale, where one indicates the most suitable habitat and zero the least suitable habitat for a species.

17.1.1 Basic Data Requirements for SDM

(a) **Occurrence data**: it is also known as 'presence' data, and it represents the geographic coordinates of areas where the species of interest have been observed. Some models also use 'absence' data, which are geographic coordinates of sites where the species is recognized not to occur.

Getting species presence data is a challenge in biodiversity monitoring. Global Biodiversity Information Facility (GBIF) plays a key role in providing taxonomic data about a country. It can be easily downloaded either from the GBIF website or the API and packages such as rgbif from rOpenSci in R with RStudio.[1] GBIF data can be accessed in simple .csv format that can be used in various software platforms and easy-to-use packages. iNaturalist is another source of species geolocation data that connects naturalists, biologists, and citizen scientists worldwide to support mapping and share biodiversity observations.[2]

(b) **Environmental data:** these represent different environment variables, i.e., temperature, precipitation, land use, elevation, etc. Elevation data can be downloaded from SRTM,[3] and further used to derive several topographic products. Diva-GIS[4] provides access to data for different countries including administrative boundaries, roads, railroads, elevation, land cover, populations, and climate database. Landcover data is available at the ESA website.[5] Columbia University's website[6] is a valuable source for a variety of global-scale data on human-modified regions, different countries' ecosystem health, and rasterized data for a population. Finally, climatic data of a much finer scale of one kilometer by one kilometer can be obtained from Worldclim.[7]

17.1.2 Preprocessing Raster and Spatial Data for SDM

The data used as predictors in SDM is mostly raster data that needs to meet some prerequisites before being used in SDM. These prerequisites include that all raster predictors should have the same spatial extent, i.e., all layers should cover the same area. These datasets should also have the exact spatial resolution, i.e., the same raster cell size. All the rasters should have the same coordinates reference system (CRS) as species presence or absence data, i.e., latitude–longitude or Universal Transverse Mercator (UTM) instead of going the other way around.

This chapter discusses various classical and machine learning approaches for species distribution modelling using the R language. It starts with the basics of using R for species modelling, then touches upon the technicalities of preparing to use R, and finally examines the data for invasive plant species for further analysis. Further

[1] https://poldham.github.io/abs/gbif.html

[2] https://www.inaturalist.org/

[3] https://srtm.csi.cgiar.org/srtmdata/

[4] http://www.diva-gis.org/Data

[5] http://www.esa-landcover-cci.org/

[6] https://sedac.ciesin.columbia.edu

[7] https://www.worldclim.org

in this chapter, various classical and machine learning approaches for SDM using R language are discussed more elaborately. Classical SDM techniques require species presence data to build predictive maps of habitat suitability. Applications of various classical models like BIOCLIM, DOMAIN, and Maxent, in R is explained in later sections, with sample code examples for better understanding. Similarly, machine learning algorithms such as the Generalized Linear Model (GLM), K-Nearest Neighbor (kNN), and Support Vector Machines (SVM) are covered. The aim is to provide the reader an overview of the available and smarter approach for existing SDM, and enable the user to choose the most applicable model to suit their purpose.

17.2 R for Species Distribution Modelling

Predicting the range of distribution of various species from their coordinate information has become increasingly straightforward with a suite of R packages, which can be downloaded and installed easily. In addition, R studio, which is an integrated development environment, is available for free download. The software also gives access to several packages that can carry out specific tasks, especially in GIS and machine learning modelling. A package once installed has to be called or activated for use each time using the function library.

Some of the commonly used packages for running SDM include:

(a) **Raster data:** raster, rgdal, and maptools.
(b) **Classical SDM mapping:** The dismo package is required for building models like Maxent and Bioclim. The red package can also be used for Maxent.
(c) **Species occurrence data:** R provides an API interface to databases through packages like rgbif (for collecting geo-referenced species occurrence data from GBIF database) and spocc data packages.
(d) **Machine learning models:** One of the most important ML packages in R is caret. Additionally, pROC and ModelMetrics were introduced for evaluation.

The example code (https://github.com/forestgeoinformatics/SmarteR, example code 1) below shows how to extract geo-referenced records for plant species such as *Impatiens glandulifera* and *Lantana camara*, which are considered invasive species in many areas. The data can be read in RStudio by installing 'spocc' package, creating a variable, and setting up an argument query that specifies a species name, a database of interest. This is useful in case if we do not want to download the species data from GBIF or from other database and just want to read it directly in the R platform. In the code, we have created a function occurrence 'occ' and have specified the scientific names of the invasive plant species. In the query, we have defined the repository as 'gbif' from where the data will be extracted. We can even concatenate different databases like gbif, ebird, and ecoengine in the same code to pull the data of interest from various sources. In the code, we added another argument 'gbifopts' that specifies that our data has coordinates. We used the function 'occ2df' to convert our data to dataframe, the result of which is shown in Fig. 17.1.

```
# A tibble: 6 x 6
  name                         longitude latitude prov  date       key
  <chr>                            <dbl>    <dbl> <chr> <date>     <chr>
1 Impatiens glandulifera Royle      173.    -43.3 gbif  2021-01-06 3017959148
2 Impatiens glandulifera Royle      173.    -43.3 gbif  2021-01-06 3017980114
3 Impatiens glandulifera Royle      173.    -43.3 gbif  2021-01-06 3017988118
4 Impatiens glandulifera Royle      173.    -43.3 gbif  2021-01-06 3018030100
5 Impatiens glandulifera Royle      173.    -43.3 gbif  2021-01-06 3018032119
6 Impatiens glandulifera Royle      173.    -43.3 gbif  2021-01-06 3018033129
> tail(data)
# A tibble: 6 x 6
  name              longitude latitude prov  date       key
  <chr>                 <dbl>    <dbl> <chr> <date>     <chr>
1 Lantana camara L.      72.5    23.1  gbif  2020-01-18 2646888022
2 Lantana camara L.      36.8    -1.19 gbif  2020-01-19 2646888095
3 Lantana camara L.      78.1    18.7  gbif  2020-01-29 2646891041
4 Lantana camara L.      72.8    19.0  gbif  2020-01-29 2646891045
5 Lantana camara L.      75.8    26.9  gbif  2020-01-30 2646891109
6 Lantana camara L.     -52.2   -12.6  gbif  2020-01-30 2646891171
```

Fig. 17.1 Result from RStudio console for extracting geo-referenced invasive plant species records

17.2.1 Working with Climate and Elevation Data in R

Some of the relevant raster datasets can be obtained directly from the R Studio interface. Different bioclimatic variables ranging from BIO1 to BIO19 that are biologically meaningful in species distribution modeling (O'Donnell and Ignizio 2012) can also be directly obtained from R platform.

In the example code (https://github.com/forestgeoinformatics/SmarteR, example code 2), we call a function to get data for different administrative boundaries for Malaysia (Fig. 17.2a, b) (Adm0 for country and Adm1 for State). We also created a variable 'climate' to get world climate data for the mean and maximum temperature at 2.5 min' resolution. Later in the chapter, we will use these administrative boundaries to clip the global climate variables for running different species distribution models.

Elevation data and its derived topographic products are important variables for SDM. Within the R environment, mosaic data for different elevation tiles and topographic products like slope, aspect, and hill shade can be created. For this purpose, libraries like 'raster' and 'rgdal' should be installed in RStudio. In addition, 'terrain' function needs to be called to compute slope and aspect. In the code (https://github.com/forestgeoinformatics/SmarteR, example code 3) we called the function raster to read our srtm raster files, function 'mosaic' is used to join these adjacent elevation rasters and pass the function 'mean' to take the average elevation value in the areas where these rasters overlap with each other. We can also save the mosaiced data (from code 'mosaicAB') to our local drive. This data is in latitude–longitude and should preferably be converted to planar units, i.e., projected coordinate system, UTM. In our example code, we projected it to UTM Zone 50 using function 'projectRaster'. We used the argument 'opt' for computing topographic products like slope and aspect. Finally, hill shade was created using both slope and aspect.

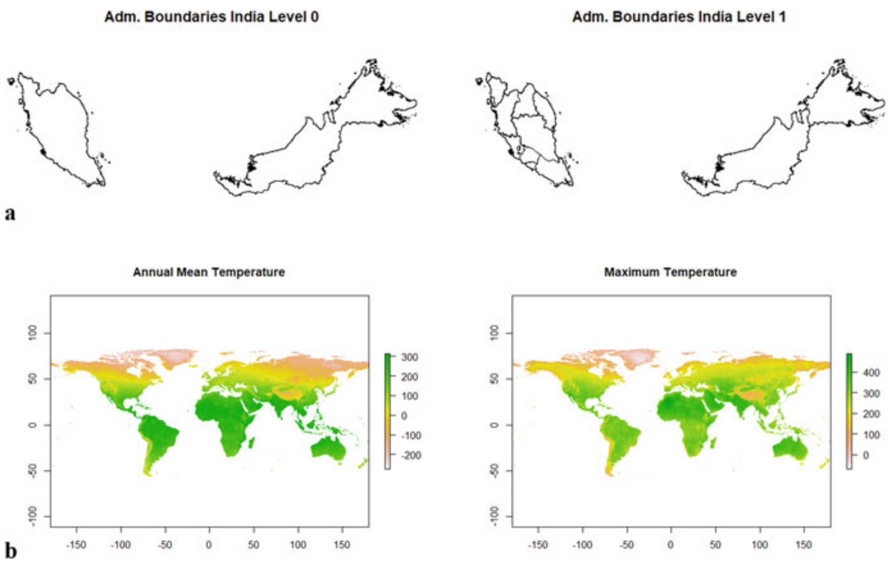

Fig. 17.2 (**a**) Result displaying the administrative boundaries and global mean temperature. (**b**) Result displaying the administrative boundaries and global mean temperature

17.3 Classical SDM Techniques

Classical SDM techniques require species presence data to build predictive maps of habitat suitability. In this section, we will discuss classical models like BIOCLIM, DOMAIN, and MAXENT. Essentially, with just the species presence data and the predictors, we can build very robust species distribution maps. SDM uses the Area under the curve (AUC) of the receiver operator characteristic that provides single number discrimination that measures how good or bad a model is. For instance, an AUC value of 0.5 indicates that the SDM is just guessing; however, a higher value indicates the greater predictive ability of the SDM. These AUC values are preferably computed using test data which is generated by either not using some points while model building or using k-fold cross-validation.

17.3.1 BIOCLIM

BIOCLIM model for species distribution is one of the very first ones that use presence-only data. It is a typical 'climate-envelopemodel'(Booth et al. 2014) that has been used for SDM to a great extent. Based on a comparison of environmental and/or climatic factors at known locations ('training data points'), the algorithm calculates the likelihood of habitat suitability to other regions. The areas with values closer to the median value (50th percentile) are more suitable. The distribution's tails are not distinguished; the tenth percentile is considered equivalent to the 90th percentile. In the R package 'dismo' implementation, the upper-end values are converted to the lower-end values. All environmental and climatic factors are compared using the minimum percentile score. An approach similar to Liebig's minimal law is used by the model. This value is subtracted from one which is then multiplied by two. Therefore, the resulting values lie between 0 and 1. This scaling method helps the results to be more like the other SDMs and thus the interpretation becomes easier. Value one is unlikely to be seen since it requires a related location with the median value of input training data for every other component included in this model's training data. A standard practice is to give the number zero to any grid cell having an environmental or climate variable value that falls outside of the 95th percentile for any one of the aforementioned parameters. In such a model, primarily climatic variables are used as predictors because climate change creates new challenges for biodiversity conservation. These models are used for describing the climate where a species currently lives that ties in with the physiology of these species, i.e., its climate "envelope." It helps to map the geographic shift of that envelope under different climate change scenarios.

In the example code (https://github.com/forestgeoinformatics/SmarteR, example code 4), we fit a BIOCLIM model for predicting '*Lantana camara*' species in Malaysia by incorporating the environmental predictors and the present locations. In the code, we read the data downloaded from gbif for Lantana species occurrence in Malaysia. The extent of our study area is defined, and we read in the library rgdal to get the bioclimatic data. The data is cropped to the extent, the map's bounding is defined, and 'bioclim' function is used to take the climatic layers. Figure 17.3 displays the impact of different climatic variables in influencing habitat suitability. We finally used the 'predict' function in the raster package to run our BIOCLIM model for habitat suitability. Figure 17.4 shows the final prediction map in which warmer colors show higher chances for lantana species to be present there.

To evaluate the model performance, background data or pseudo absences are required; however, in most cases, we do not know where the absences might be. So, a matrix of pseudo absences needs to be created to determine if the model can differentiate between the suitable habitat and the background. Random points (background points or pseudo absence points) are extracted from the predictor rasters.

The example code (https://github.com/forestgeoinformatics/SmarteR, example code 5) shows how to create pseudo-absence data and evaluate the model performance. We created 1000 random background points from the predictors. The function 'evaluate' was used along with four arguments 'presence', 'background', 'model', and 'predictors' to calculate the important AUC matrix which tells how good our model is performing.

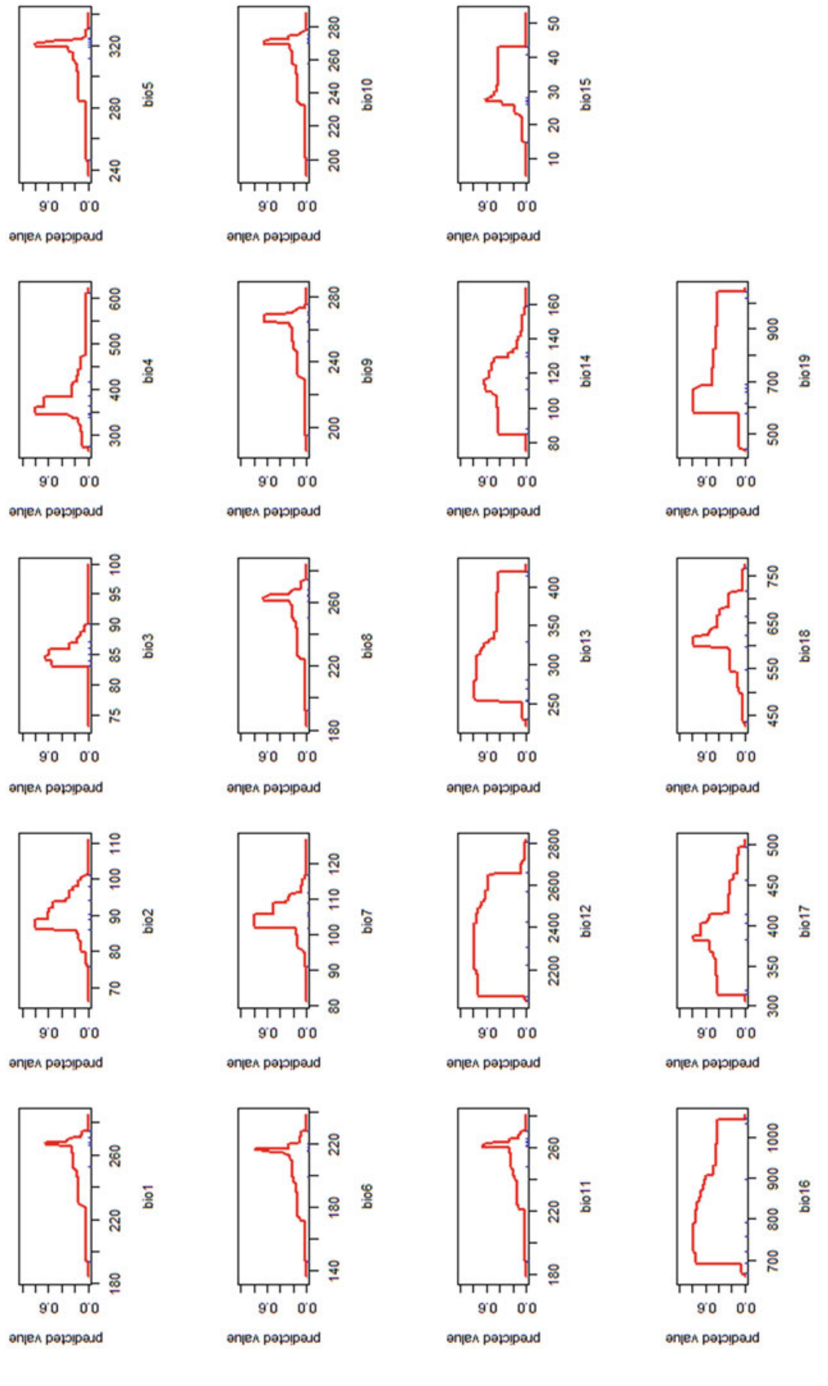

Fig. 17.3 The impact of different climatic variables in influencing the habitat suitability

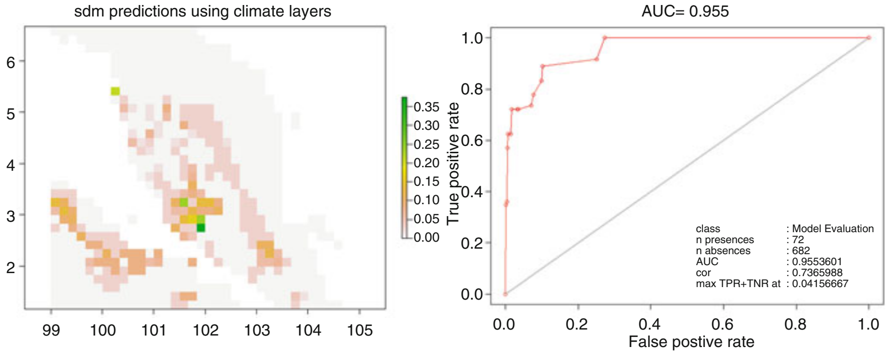

Fig. 17.4 BIOCLIM SDM predictions using climatic layers and model evaluation result (AUC = 0.95)

17.3.2 MAXENT SDM in R

Maximum Entropy (Maxent) is the most extensively used species distribution model. Elith et al. (2011) explain the algorithm based on the maximum entropy for modelling species ecological niches and distribution from environmental variables, i.e., climatic variables or land-use factors. Maxent is developed in Java, therefore it is available as machine-independent executable program.

Maxent, short form of maximum entropy, modelling begins with the notion of uniformity. The approach further utilizes weighted constraints to the distribution that are built on the relationship between response and predictor variable. It adjusts the weighted constraints weights iteratively till the point of optimal distribution is achieved and finally generates spatially explicit predictions from the given inputs (Phillips et al. 2006; Elith et al. 2011).

Kumar et al. (2020) researched various invasive plant species in India and the use of different SDM techniques for mapping their distributions (Table 17.1). Adhikari et al. (2015) mapped invasive plant species hotspots for entire India using 155 data points of invasive species occurrences derived from the GBIF. They modeled the potential sites using anthropogenic biome (www.sedac.ciesin.columbia.edu), bioclimatic variables (www.worldclim.org) and ecoregion (www.maps.tnc.org) and, as the input predictor variables at a spatial resolution of 4 km, i.e., 0.04° using the Maxent model. They modeled high and low suitable regions governed by the climatic variables. These regions were found to be intersected with the known anthropogenic biomes and also with the ecoregions of the country and were classified as "Hotspot" of invasive alien plant species. Padalia et al. (2015) used the Maxent model to predict the potential regions of attack by Hyptis under future climate scenarios of the year 2050 for Southeast Asia, North and South America, Africa, and Australia. They used the GBIF archive of species occurrences and data from the national inventory of biodiversity (http://bis.iirs.gov.in/bid1.php) of Hyptis and 20 environmental predictors at a grid cell size of 5 × 5 km. Padalia and Bahuguna (2017) used the Maximum Entropy model to predict multiple invasive

Table 17.1 Selected literature on mapping of invasive species using SDM techniques in India (Kumar et al. 2020)

Target species	Study region	Brief description	Reference
Hyptis suaveolens	Entire India	The study compared mapping accuracy of two species distribution models, viz., GARP (Stockwell 1999) and Maxent (Phillips et al. 2006)	Padalia et al. (2014)
155 invasive species	Entire India	Used maxent model to map hotspots of invasion	Adhikari et al. (2015)
Hyptis suaveolens	Africa, Asia, Australia, North America and South America	Mapped potential sites of attack using Maxent under future climate scenario of the year 2050	Padalia et al. (2015)
Mikania micrantha and *Mimosa diplotricha*	Rajiv Gandhi Orang National Park (RGONP), Assam	Modelled the probable distribution of invasion using Maxent	Choudhury et al. (2016)
98 invasive species	Part of Central India represented by Deccan Peninsula	Modelled hotspots of invasion using Maxent	Padalia and Bahuguna (2017)
Lantana camara and *Cassia tora*	Entire India	Different models like the generalized linear model, generalized additive model, and maxent to map current patterns and risks of invasion under future climate scenarios of the year 2050 and 2100	Panda et al. (2018)
Yushania maling (Maling bamboo)	Part of Darjeeling Himalaya, West Bengal	Used Maxent, GARP, BIOCLIM Martin (1996)and their ensemble to map the potential sites of invasion	Srivastava et al. (2018)

plants' hotspots with occurrences of selected 98 invasive plant species for central India, represented by the Deccan Peninsula (Central highlands, Central plateau, Chotta-Nagpur, and Eastern highlands) along with the Semi-arid zones of Rajputana province. Choudhury et al. (2016)used Maxent to model the likely distribution of two invasive plants species, i.e., *Mikania micrantha* and *Mimosa diplotricha* in Rajiv Gandhi Orang National Park, Assam, which characterizes a protected tropical grassland.

To run the Maxent model in R, we need to download the software from (https://biodiversityinformatics.amnh.org) and copy the maxent.jar file to your R folder's win-library at the appropriate version level. You will have to copy it in the java folder of your 'dismo' installation package (example: This PC\Documents\R\win-library\4.0\dismo\java\maxent.jar). It is important to note that one needs to install the rJavalibrary for proper implementation of Maxent model in R. In the example code (https://github.com/forestgeoinformatics/SmarteR, example code 6), we fit a Maxent model to predict the '*Lantana camara*' invasive plant species in Malaysia using various predictors and the presence locations. Read in the libraries like 'raster',

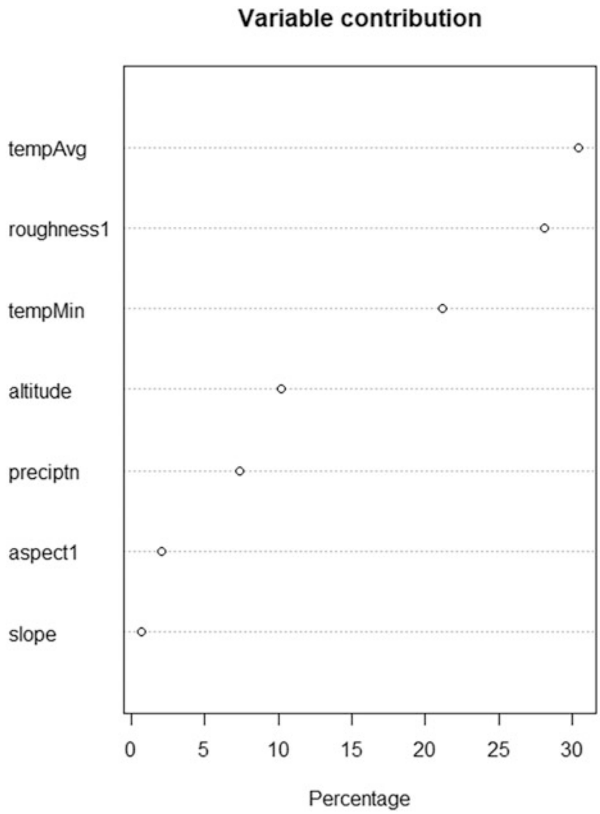

Fig. 17.5 Contribution of different variables in Maxent modelling. Average temperature contributes highest with 30%

'rgdal' and 'dismo'. A working directory is set up along with an empty raster stack used to store raster layers. The for loop is used to create the temp rasters one by one that are finally used to create the raster stack. Using kfold, the presence data for Lantana species is split into five portions that are used for building test models. Using 'maxent' function, the model is first run-on presence-only data. Figure 17.5 plots different variable importance, and it shows that average temperature is the most important variable (explains 30%) to determine the species habitat suitability. We create pseudo-absences for training model performances. Using the 'evaluate' function, we find that 'Area under the curve' (AUC) is 0.95, which means this is a robust model. We use the function 'predict' and use Maxent model to apply on the stack of rasters to predict species distribution (Fig. 17.6 where darker colors represent higher suitability area).

17.3.3 DOMAIN SDM in R

The DOMAIN SDM technique ciphers the potential distributions using a point-to-point similarity metric (Gower metric) to allot a classification value to a candidate

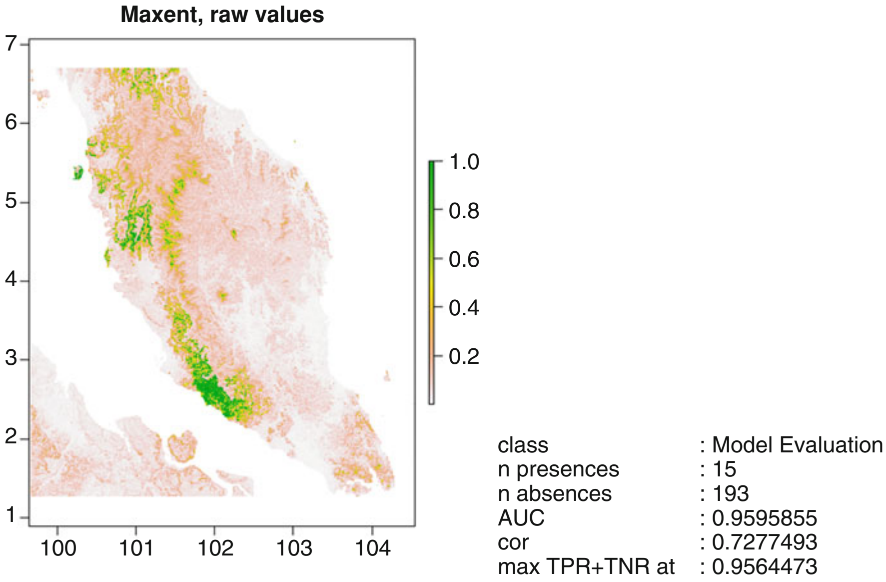

Fig. 17.6 Maxent SDM predictions using bioclimatic and other raster layers (AUC = 0.95)

site based on the nearness in the environmental space of the most similar record location. DOMAIN model can be targeted to use the mean of several largest similarity values rather than the maximum similarity value, if there happen to be serious outliers in the data. This model is most suited to applications where the available site location data or environmental data are limited.

The DOMAIN model assumes that (1) the species occurrence data signifies an unbiased distributed sampling of the complete range of environmental conditions, i.e., including all the possible environmental variations in the modelling and prediction and (2) the environmental predictors are computed without error. However, it is essential to note that the potential distribution maps generated with help of this model may indicate some degree of data collection biasness.

DOMAIN only requires records of species presence and performs well when species occurrence data is scarce. Since the DOMAIN method uses point-to-point distances for each pixel, it performs better when all the records are closer together in environmental space.

Envelope-based methods delimit niche boundaries in the environmental space composed of multiple dimensional, where each dimension corresponds to a predictor variable (Pulliam 2000; Peterson 2006). The distance-based methods (e.g., DOMAIN) are similar to envelope models which operate in environmental space; however, instead of computing niche boundaries, they quantify environmental distances (i.e., similarities or resemblances) between the areas of known invasion occurrence and other areas (Barry and Elith 2006; de Siqueira et al. 2009).

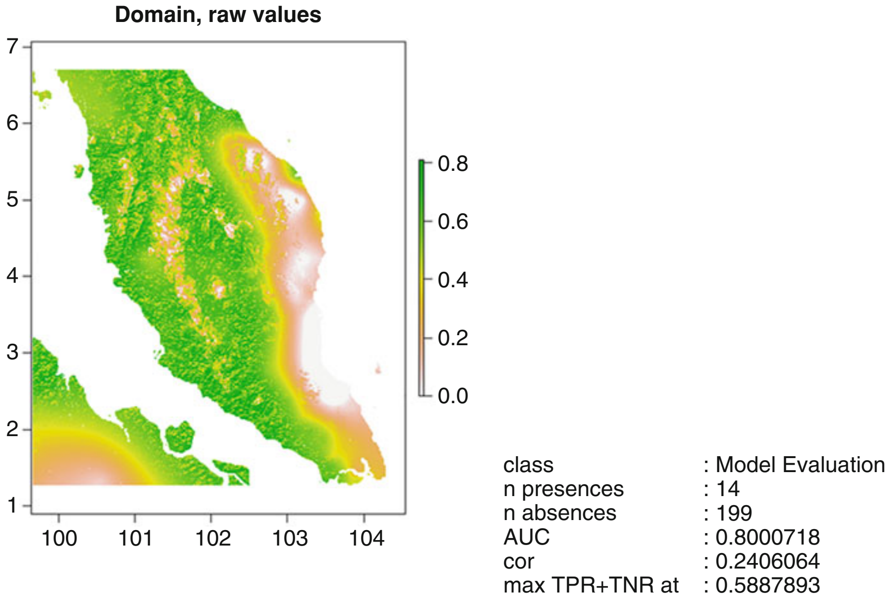

Fig. 17.7 DOMAIN SDM predictions (AUC = 0.80)

The example code (https://github.com/forestgeoinformatics/SmarteR, example code 7) runs DOMAIN model for predicting *Lantana camara* distribution in Malaysia. We need to read in libraries such as sp., raster, dismo, and maptools. We create a variable 'datafiles' to store all our raster predictors with an extension .tif. An empty stack is created to store the raster files. All rasters are read one by one in empty raster by iteration and then stacked together in the variable called 'stck'. We then use the 'kfold' cross-validation to better evaluate our model performance. We create the training data, testing data, and the 1000 random background points. To carry out modelling, we will call the function domain from the dismo package. We get the AUC of 0.8 which tells that our model is robust. To build an actual predictive model, we use the function 'predict' with the raster predictors, domain model, and the extent (Fig. 17.7).

17.4 Machine Learning Models for Habitat Suitability

Machine learning is a robust tool for mapping the most suitable habitats and identifying an algorithm that accurately models the species distribution. Machine learning is a subfield of artificial intelligence (AI) that deals with the development of systems that learn from data rather than from explicitly coded instructions (such as those used in traditional programming). Machine learning methods have been increasingly used in recent years for building predictive habitat suitability maps through a series of non-parametric methods. Based on the given data, these approaches may create regression or classification functions. Complicated interactions between predictors may occur in vast volumes of data, and machine learning approaches can interpret nonlinear relationships between predictors as well as complex data (Recknagel 2001). Some of the standard machine learning algorithms include: Lazy learning algorithms (KNN-supervised learning), Support vector machines (for classifications and regressions), Tree-based ensemble classifiers (Gradient Boosting and Random forest algorithm), and logistic regression with binary response variables. Machine learning algorithms require both the presence and absence of data.

We build the machine learning models (classification or regression) on one dataset known as training data. The model's ability to predict labels based on predictor values (classification) or based on the response variable values (regression) is carried out using test data. We need to test this to test the model's generalizability. There can be a case of model overfitting (random error) if the model is very complex. Approaches like model testing on hold-out test data or cross-validation can help detect this overfitting. As discussed earlier, there are some prerequisites to running a machine learning model in R, i.e., all raster predictors should have the same extent, same resolution, and also be in the same CRS.

We will discuss different machine learning models and their applications for predicting invasive plants distribution, i.e., *Lantana camara* distribution in peninsular Malaysia.

17.4.1 GLMs for Habitat Suitability

Regression analysis using a generalized linear model (GLM) is a simplification of conventional least squares regression. Models are fit using simple linear relationships between the variables. With a link function, the linear model may connect to the response variable, allowing each measurement's variance to be evaluated in relation to its projected value. Multiple linear regression equations, Poisson regression, or logistic regression may all be interpreted as GLMs, depending on how they are characterized. Multiple regression analysis using a binomial distribution and logistic linkages is an extension of GLM. Polynomials of a higher degree may be fit into it. A weighted sum of ecogeographical predictors explains the dependent variable (species presence or absence). The weights are adjusted to create the best possible fit between the designated model and the calibration data set (Nicholls 1989; Jongman and Jongman 1995). Guisan et al. (2002) provide an overview of the species distribution modelling using GLM. In R, the 'glm' function provides the implementation for the GLM and the link function. The error distribution is stated with the 'family' argument.

We run the logistic regression when we have binary response variables, i.e., 1 and 0 (presence and absence). In the example code (https://github.com/forestgeoinformatics/SmarteR, example code 8), 'pb' is our response variable that stands for species presence and background. We will work with library 'caret', set seed for pseudo-repeatability, use 80% of the data for model training and 20% for the

```
Coefficients:
                Estimate Std. Error t value Pr(>|t|)
(Intercept) -6.080e+00  9.460e-01  -6.427 3.44e-10 ***
altitude     1.679e-03  2.412e-04   6.961 1.26e-11 ***
aspect1     -5.003e-05  1.528e-04  -0.327  0.74349
land         6.604e-05  3.314e-04   0.199  0.84214
preciptn    -8.081e-04  2.555e-04  -3.163  0.00167 **
roughness1   4.149e-04  4.058e-04   1.022  0.30713
slope       -9.252e-08  9.131e-08  -1.013  0.31153
tempAvg      3.989e-03  3.534e-03   1.129  0.25955
tempMin      2.431e-02  3.442e-03   7.062 6.57e-12 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for gaussian family taken to be 0.09431769)

    Null deviance: 51.124  on 441  degrees of freedom
Residual deviance: 40.840  on 433  degrees of freedom
AIC: 221.65
```

Fig. 17.8 Factors influencing the GLM model (stars signifies that these model predictors are statistically significant)

model testing. We can fit a glm model using a 'base' package with variable 'm1' and model-building training data. Fig. 17.8 lists the factors influencing the GLM model where stars signify that these model predictors are statistically significant, i.e., these factors are influencing the species presence and absence at a given location.

17.4.2 Support Vector Machines

SVMs employ a simple linear technique to fit the data. SVMs are also non-linearly associated to the input space in a high-dimensional feature space; however, in practice, it does not include any calculations in that high-dimensional space (Vapnik 1998). This simplicity, pooled with state-of-the-art performance on numerous learning problems (regression, classification, and novelty detection), has mainly contributed to the attractiveness of the SVM (Karatzoglou et al. 2006). They were first used in SDM by Guo et al. (2005). There are several implementations of SVM in R, and the most useful ones are probably the function 'svm' in package 'e1071' and the.

'ksvm' function in package 'kernlab'. 'ksvm' includes multiple SVM kernels and formulations provide beneficial features and options like a different technique for plotting. However, it lacks an appropriate model selection tool. The package 'e1071' provides the 'svm' function and it also includes a model selection tool: the 'tune' function (Karatzoglou et al. 2006).

In the example code (https://github.com/forestgeoinformatics/SmarteR example code 9), we ran svm model for *Lantana camara* species in peninsular Malaysia. The presence, absence, and land use data can be turned into factors. We can create data partition from 'caret' package (75% training and 25% testing). In train_control, we

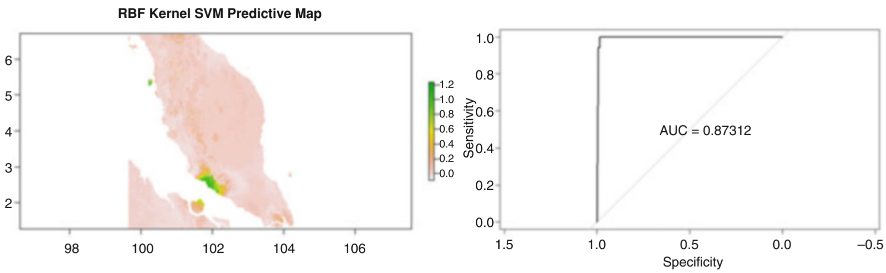

Fig. 17.9 Support Vector Machine SDM predictions (AUC = 0.87)

define ten-fold cross-validation. We ran support vector classification with RBF kernel (using method 'svmRadial'), which gives the best performance. We can test the importance of different factors using the variable 'varImp'. We test the model by predicting 'mod_fit1' on the testing data and use the library pROC to create the area under the curve (AUC). With the high AUC value of 0.87, the model seems to be quite robust. We implemented our SVM model on the stack of rasters to create the species distribution map (Fig. 17.9).

17.4.3 K Nearest Neighbor (kNN)

kNN is a good example of a supervised learning technique that requires data to be fed based on the classifications. The model can be tested on an unseen dataset to gauge the model's success in predicting existing classes on the data provided based on the trained algorithm. All instances are stored in the kNN database and fresh cases are classified based on a similarity measure (distance function). Therefore, the kNN algorithm inspects through the training data before classifying an unseen dataset using a trained algorithm and finds the k training examples closest to the new example (Hollings et al. 2017). It then attributes a new example with a class label based on a majority vote between those k-training examples, i.e., if k equals to 1, the class label will be allotted based on the nearest neighbor. However, if K equals 3, then the algorithm will select the nearest three data points available within each case and classify them based on a majority vote depending on the classes that those three neighboring points hold. The average value of the k nearest neighbors is the output of the k-NN for regression. K-NN model was fitted and ran for *Lantana camara* in the example code (https://github.com/forestgeoinformatics/SmarteR, example code 10). Data partition (75% for training and 25% for testing) was created with presence-absence data as the basis for partitioning. 'pb~.' means we want to use all the predictors to be included in our model with method 'knn' from the 'caret' package. Variable 'varImp' determines the significance of different predictors, and library 'Proc' is used to compare the testing data with predicted responses. The results displayed in Fig. 17.10 show that 'precipitation' is the most important predictor and the AUC value of 0.78 depicts that our model is good.

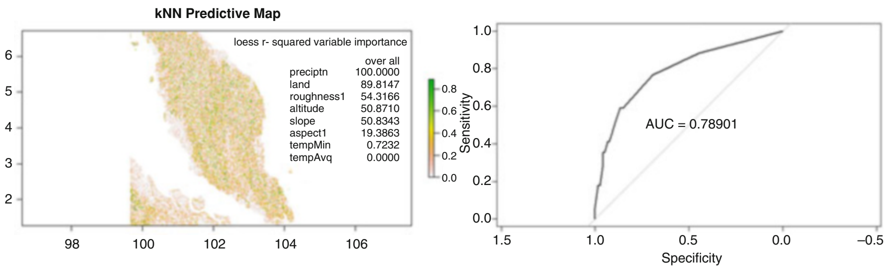

Fig. 17.10 KNN Predictive Map and variable importance (AUC = 0.78)

17.4.4 Random Forest (RF)

The Random Forest technique has been widely accepted in recent years (Cutler et al. 2007) and it can produce robust results for mapping individual species (Evans and Cushman 2009).The random forest method has good performance for SDM techniques for several reasons: (1) it is non-parametric and therefore flexible in terms of the available explanatory variables that it can manage; (2) it can display nonlinear relationships between the response and explanatory variables and also hierarchical interactions of the explanatory factors; and (3) it uses the data on species presence and absence, a valuable feature when complete data are available. The key principle behind ensemble/tree techniques is that a group of "weak learners" can form a "strong learner." Each classifier, individually, is a "weak learner," while all classifiers collectively are a "strong learner." The random forest starts with a standard machine learning technique called a "decision tree" which, in ensemble terms, relates to a weak learner, and the random forest is a strong learner.

The Random Forest (Breiman 2001) technique is an extension of Classification and Regression Trees (CART) (Steinberg and Colla 2009). In 'R', it is well implemented in the package 'randomForest' with similar function name 'randomForest'. The 'randomForest' function takes a formula or, in two arguments separately, a vector with the response variable and dataframe with the predictor variables. However, if the response variable is a factor (categorical), implicitly randomForest will do classification; or else, it will do regression (Hollings et al. 2017). Random forest gives a robust performance with binary classification problems like those about species distribution maps.

In the example code (https://github.com/forestgeoinformatics/SmarteR, example code 11), we ran the robust random forest algorithm for predicting the distribution of *Lantana camara* in peninsular Malaysia. The response variable 'pb' stands for species presence and absence. We use the predictors like land, altitude, aspect, precipitation, roughness, slope, and temperature (average, minimum) for running our species distribution model. The response variables 'pb' and 'land use' are declared as factors using the function 'factor'. We work with library 'caret' and create a data partition. We define training control as a ten-fold cross-validation. In our model, we use the method 'rf' (random forest), and we add an argument

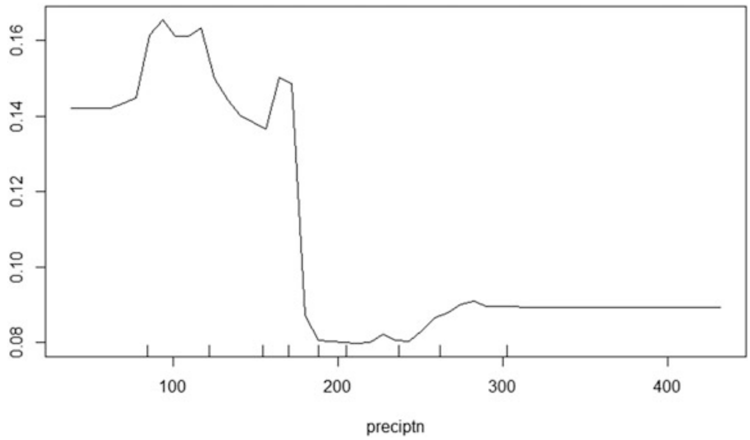

Fig. 17.11 Graph displaying the partial dependence of predictor 'precipitation'. With higher precipitation, the habitat predictability decreases

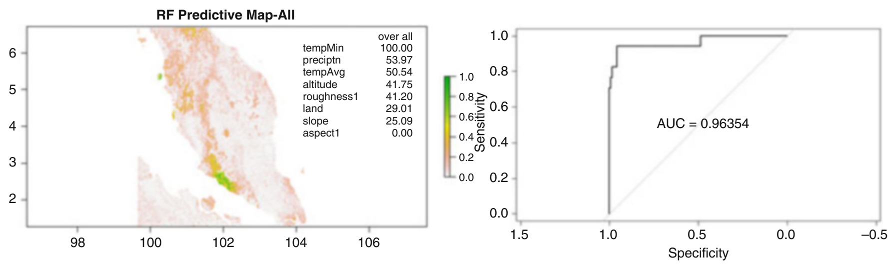

Fig. 17.12 Random Forest SDM prediction map (AUC = 0.96)

'importance = TRUE' to get the importance of the predictors. The results show that 'Minimum Temperature' is the most important predictor followed by precipitation. Using 'partialPlot' function, we can see how an individual predictor influences the species prediction results (Fig. 17.11). We use library 'Proc' to test the model fit, and as seen from the graph (Fig. 17.12), the model looks very robust with an AUC value of 0.96.

17.4.5 Gradient Boosting Machine (GBM)

Boosted Regression Trees (BRT) was developed and implemented by Friedman (2001), who mentioned it as a 'Gradient Boosting Machine'. It is also identified as a 'Gradient Boost', 'Stochastic Gradient Boosting', and a 'Gradient Tree Boosting'. The technique is implemented in R through the 'gbm' package. Elith et al. (2008) describes the use of BRT with reference to SDM, accompanied by several 'R' tutorials along with examples using different functions variations. The same functions have been marginally tuned and included in the 'dismo' package. These functions extend the ones in the 'gbm' package to simplify application to ecological data and improve interpretation.

In the example code (https://github.com/forestgeoinformatics/SmarteR, example code 12), like the previous techniques, we ran GBM on *Lantana camara* invasive plant species data for peninsular Malaysia. We use 'caret' package to define training control (ten-fold cross-validation). In this model, we used the method 'gbm' to run on all the predictors. We plotted the bar graph of the relative influence that shows that Minimum temperature is the most important predictor. The AUC value of 0.96 proves that our model is very robust. From our code, we also plotted the graphs for a couple of partial dependence predictors (Fig. 17.13 a, b, c).

17.5 Conclusion

Predicting the species habitat range from their geolocations has become easier with a smarter suite of R packages. There are two types of SDM techniques: those that rely on just presence data and those that rely on both. This chapter illustrated a brief overview of the SDM concepts and an introduction to the main modelling steps. We used practical code examples for different SDM approaches that we executed and analyzed for invasive plant species (*Lantana camara*). We learned about packages for SDM, downloading, and preprocessing datasets (presence-absence and predictors), running different SDM methods, and visualizing the model predictions in the process.

A paramount concern in SDM is that the species occurrence data adequately represents the species' geographic spread under study. This implies that species identification and location information should be accurate for establishing the relationship between species and their environmental predictors. One assumption is that we have ideally sampled both these datasets and incorporated all significant factors that determine species range limits. This is questionable as the species show transient dynamics due to several factors (Urban et al. 2016; Zurell 2017). The observation process can also bias our ability to detect specific details (Guillera-Arroita 2017). Therefore, the underlying assumptions and known biases should be taken into account for improving the modelling approaches.

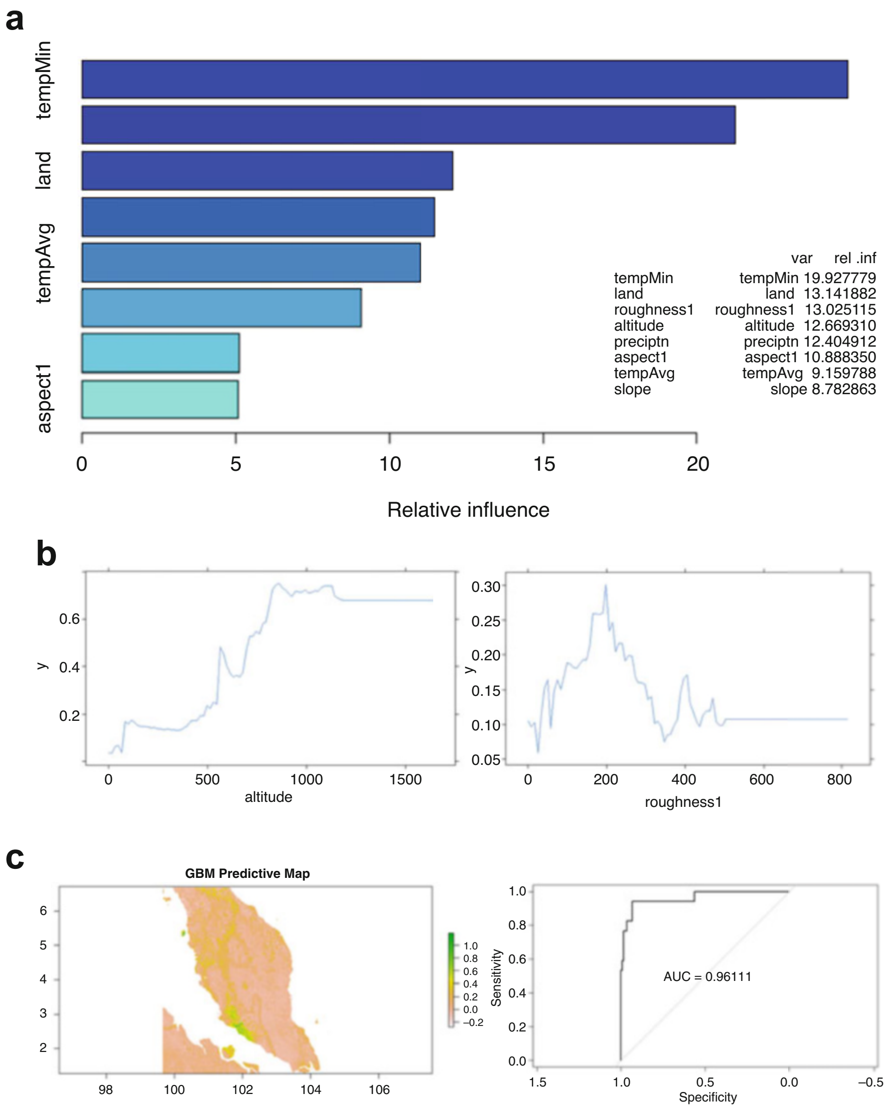

Fig. 17.13 (**a**) Relative influence of different factors. (**b**) Partial dependence plot for Altitude predictor and Partial dependence plot for roughness predictor. (**c**) GBMSDM prediction map (AUC = 0.96)

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Mapping and Identification of Trees Using Semantic Segmentation Deep Learning Neural Network

18

Ram Kumar Singh, Agnish Kumar Das, Harshi Jain, Prafull Singh, and Pavan Kumar

Abstract

Mapping different tree species based on their canopy characteristics is a challenge with the high spatial resolution data. We present an artificial intelligence-based semantic segmentation deep learning method to map and identify Mango and Coconut trees. The semantic segmentation method is based on Convolution Neural Network-(CNN)based method, which trains its model using chips and labels of the object. Model validation is carried out using learning, and accuracy is validated using the given chips and labels. The semantic model is used on the independent chip to obtain the mapped image. The model's capability to identify the object on the basis of canopy shape, structure, density, and pixel statistics makes it extremely useful for the mapping and identification of single and multiple tree species. We used U-Net model for mapping two different species of trees in two different sites of India. The model validating accuracy obtained was fairly good in the range of 81–82%. The validation of trees using ground census data is around 82% and canopy area validation is in the range of 78–80%. The trained model performs automatic identification of trees for identical images, but if the type of image is changed, the model needs to be retrained. The advantages of this method make it useful for the identification of tree species

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inside and outside the forest. The method has the potential to be utilized for studies of paramount importance like the census of trees, identification, and mapping of agricultural crops.

Keywords

Forestry · U-Net model · Convolution Neural Network (CNN) · Tree census · Artificial intelligence · Machine learning

18.1 Introduction

Forestry, as a scientific discipline, emerged only after the mid-nineteenth century. Previous to its emergence as a scientific discipline, and a field of research, the history of forests across the world was primarily of destruction. Forests initially gained attraction predominantly for the colossal amount of services that they could provide through fodder, timber, fuelwood, etc. The primary scientific development in the forestry sciences came through silvicultural practices. The principles which are implemented to control the establishment, structure, composition, and growth of a forest is termed *silviculture* (Baker et al. 1999). Silviculture, a tool for forest management, has also undergone multiple changes through the years. While silviculture methods have in the past resorted to uncontrolled exploitation, the blooming of civilization in the modern age, and the consequent dwindling of forests have made forest managers across the globe to rethink the methods for managing forests. In the present day, a more sustainable approach is being adopted for managing the forests. Furthermore, with the industrial age dominating dynamics in most fields, newer problems have emerged with regard to forests. These problems warrant innovation and implementation of newer technologies which would guarantee limited human intervention.

The forests and forest species are under threat due to multiple reasons. Major problems that exist for the foresters include fire (Frolking et al. 2009), invasive alien plants (Travis and Park 2004), an increase in the number of threatened species (Wright and Muller-Landau 2006), decrease in the number of economically important plant species (Sher et al. 2010), habitat loss for specialist species (Helm et al. 2006), etc. These issues necessitate monitoring on both temporal and spatial scales, which is both logistically and fiscally challenging. Monitoring the range of a vulnerable species, for example, necessitates knowledge of its spatial range as well as the conditions that promote its expansion. As a result, the species must be mapped, and a species census is also necessary. New technological breakthroughs, such as satellite remote sensing and artificial intelligence, have made it much easier for humans to complete these duties.

With the introduction of such technologies, an attempt must be made to strike a balance between traditional approaches and newly developing technology. As a result, a new scientific field known as "digital forestry" has emerged. The science, technology, and art of methodically obtaining, integrating, evaluating, and applying digital information to promote healthy forests has been termed as "digital forestry" (Tang et al. 2006). Its main goal is to use digital tools to explore and comprehend the history, current state, change, and future of forest resources and the surrounding. The area of digital forestry actively employs the broader domain of *Artificial Intelligence* and its linked components, machine learning and deep learning, in conjunction with satellite remote sensing, for the goal of addressing forestry concerns such as tree mapping.

Artificial Intelligence, which has emerged due to the advances in machine learning and process automatization (Boon et al. 2018), helps us to solve many real life complex problems (Nayak and Dutta 2017). It is a challenge to map, identify, and conduct a census of trees with the available images obtained from space-borne satellite datasets and other platforms (Singh et al. 2021). The identification of various tree species and their stages on the basis of their canopy shape, size, structure, and density can be performed periodically with visual expert interaction (Joshi et al. 2006). The deep learning method trains the model to develop intellect which helps in testing and identifying the class objects. It will lead to the automatization of the process for independent data which shows similar behavior, and this will help in identifying the class objects with minimal interference.

With the other classifiers which map, identify, and classify objects (Decision tree, Pixel-based hard classifiers, Object-identification methods, Logistic regression, Bayesian-classifiers, Hyperspectral classifications, and basic modelling), the entire process needs to be reinitiated each time (Joshi et al. 2006). The artificial intelligence deep learning methods preserve its model intellect, and reinitiating of processes need not be done. After training, and forming the model intellect, it needs to be tested with current datasets. The efficacy of artificial intelligence deep learning methods has been checked in various fields, namely, detection of cancer (Hu et al. 2018), biomedical science (Dash et al. 2020), automatic voice and face identification (Sun et al. 2015), vehicle identification (Liu et al. 2016), land cover-based identification (Helber et al. 2019), and animal census (Norouzzadeh et al. 2018). For real time continuous identification of objects, the performance and efficacy of deep learning methods are better than the other methods, and it has acceptability in most fields.

The identification of trees is important to track precious trees, conduct census of trees, locate medicinal plants, etc. It helps us to identify the endangered species of plants and calculate the biomass of trees (Zhang et al. 2019). Managing a forest and non-forest region inventory for a large area is difficult and time-consuming without the employment of the latest techniques (Otero et al. 2018). The deep learning methods work like supervised classification techniques. The model is trained on the basis of given data, clues, class-area of interest (AOI), image chips, object size, and structure to build its own logic, which is based on the statistical information of selected pixels. This has eliminated the need for manual tracking which used to be previously employed to monitor and assess damages to the forest (Hamdi et al. 2019).

18.2 Deep Learning Models

18.2.1 Origin of Deep Learning

Artificial intelligence led to the emergence of machine learning in the 1950s (Alom et al. 2018). Machine learning has grown in popularity in a variety of fields over the years and it has also spawned other focused disciplines such as neural networks. Neural networks are a subfield of machine learning, which eventually led to the emergence of deep learning (Fig. 18.1) (Alom et al. 2018). Deep learning, as a technique emerged as recently as 2006, and the first convolution neural network model to be created was AlexNet by Krizhevsky et al. (2012).

Following its inception, deep learning has exhibited a stupendous proclivity for success in all the fields it has been applied in. The approaches that have evolved in deep learning involve a supervised approach, semi-supervised approach, partially, and unsupervised approach (Alom et al. 2018). Another novel approach that emerged out of the deep learning technique is reinforcement learning.

Supervised learning involves the usage of labelled data. In this method, the model needs to be trained using labelled datasets, and the model would then prepare a set of inputs and a set of corresponding outputs. After successful training, the model would be able to provide the answers to the necessary queries (Alom et al. 2018). Supervised learning includes Deep Neural Networks, Convolutional Neural Networks, etc. Semi-supervised learning is a procedure wherein the system does not require a completely labelled dataset for training, and a partially labelled dataset suffices (Alom et al. 2018). These include networks such as the Generative Adversarial Networks. Unsupervised learning involves the systems which function without the presence of data labels. Unsupervised learning helps in untwining unknown structures in the input data. It frequently uses clustering techniques to provide the

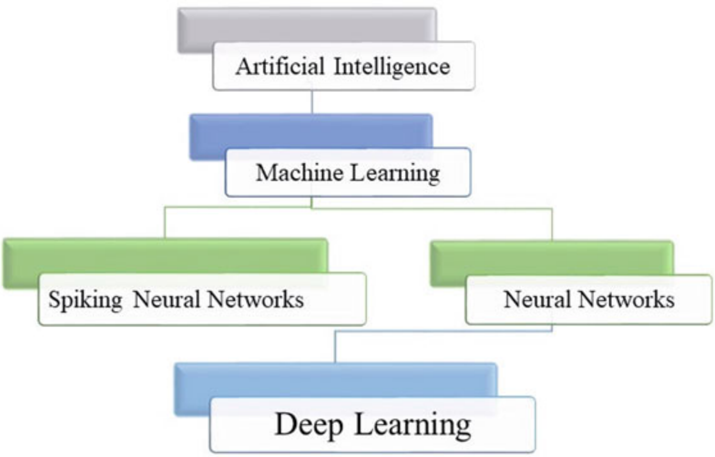

Fig. 18.1 Evolution of deep learning (adopted from Sze et al. 2017)

necessary output. The Auto Encoder and Restricted Botzmann Machine are prominent examples of deep learning systems which employ unsupervised learning (Alom et al. 2018). The reinforcement learning technique is a comparatively newer system which finds enormous applicability in unknown environments. In reinforcement learning, the function being optimized cannot be accessed in its entirety, and this is the fundamental distinguishing factor between supervised and reinforcement learning (Alom et al. 2018).

Deep learning methods have paramount applicability in situations where a human expert is absent, the solution of the problem changes temporally, solution needs to be modified to specific scenarios, and when the size of the problem is too large for human comprehension.

18.2.2 Functioning of Deep Learning in Object Identification

Unlike state-of-the-art machine learning approaches, deep learning models automatically learn characteristics from images. Deep learning has become popular among researchers in recent years for processing remote sensing data (Krizhevsky et al. 2012; Virnodkar et al. 2020). A deep learning classifier processes the image, without any preprocessing and modification. Although it needs the image of specific size and extent, i.e., multiple of 256-pixel × 256-pixel, due to limitations in the size and extent of the image that can be used for training, and for fast performance. For better accuracy, contrast, intensity, and radiometric enhancements should be applied to both training and testing images. The enhancements are generally avoided if independent data and augmentation techniques are used in the process. It has higher object identification accuracy and is able to avoid any imprecision in the size and extent of training data (Suzuki 2017). The machine learning and deep learning methods follow the concept of artificial neural network (ANN). The deep learning methods used for object-based identification use the features of engineering processes. Certain typical hidden processing layers are derived and checked, which carries more statistical operations as compared to machine learning-based methods (Ibtehaz et al. 2020). Machine learning is used for data-based classification, and is not oriented for object-based identification (Goodfellow et al. 2016).

Recently, deep learning (DL) technology has achieved astounding results in crop and land use land cover (LULC) classification from remote-sensing time series images, in particular, the Convolutional Neural Networks (CNN) algorithm (Virnodkar et al. 2020). CNNs are becoming more common as a result of their impressive achievements in a variety of fields, including remote sensing (Krizhevsky et al. 2012). This is due to the image's stationary characteristic, which stipulates that contents retrieved from one region of an image can also be applied to another. CNN architecture consists of multiple layers, including convolutional layers (which include processing units, i.e., neurons), sub-sampling layers, and fully connected (FC) layers with nonlinear transformations. The convolutional layer operates as a function to extract features from previous layers of the network, and each layer creates feature maps as an output (Virnodkar et al. 2020).Advanced deep learning methods such as CNN (LeCun et al. 1998) have, since their inception, dominated the field of image analysis and computer vision. The phenomenon is capable of advance localization (Krizhevsky et al. 2017), classification of objects (Sermanet et al. 2013), and making radical progress in object identification (He et al. 2016a, b). A number of CNN models have been developed in the recent past which can be used for classification and mapping of trees.

18.2.2.1 AlexNet

The AlexNet model was developed by Krizhevsky et al. (2012). This network has eight hidden layers in total, comprising five convolutional layers, three max pooling layers, and three FC layers. The rectified linear unit function was used to increase nonlinearity, and local response normalization was performed after the first and second convolutional layers. The final FC layer is followed by a softmax activation layer. AlexNet's success was due to the utilization of graphics processing units (GPUs) for convolution operations, the use of dropout to overcome overfitting at FC layers, non-saturating neurons, and more training examples. Furthermore, it necessitates fewer parameters, namely, 60 million and 650,000 neurons (Virnodkar et al. 2020), which minimizes network training time. Each layer generates feature maps as an output.

18.2.2.2 ResNet50

ResNet is a neural network developed by He et al. (2016a, b) which made massive improvements from the previous neural networks that existed. In addition to the difficulties of training deep networks, they all suffered from the major issue of vanishing gradient, which renders learning minuscule because it is backpropagated while being in the earliest layers. Few deep architectures attempted to solve the vanishing gradient problem prior to ResNet. ResNet, on the other hand, was successful by incorporating skip connections, which skip a single or multiple layers in the network, a method utilized by other networks as well. ResNet has been observed to have the ability to work well with remote sensing data (Virnodkar et al. 2020).

18.2.2.3 DenseNet

DenseNet refers to the Dense Convolutional Network which was developed by Huang et al. (2017). As a result of its extensive connectedness, DenseNet obtained higher accuracy with fewer parameters than ResNet. The input image is initially convolved using 16 output channels and then sent to the dense block in DenseNet. In a feed forward method, every layer in each dense block is connected to every other layer in the block. Each layer collects information from all preceding layers and outputs it to all subsequent layers. To produce the final result, all feature maps gathered from previous layers are analyzed separately at each layer and concatenated in a single tensor.

18.2.2.4 U-Net

The U-Net model (Ronneberger et al. 2015) illustrates the workflow structure of semantic segmentation. Semantic segmentation is a deep learning method that is transformed by CNN for a more instinctive performance of object identification. The left upper part of the model represents how the network is trained for image identification and classification and is used by any other deep learning methods ResNets and others. The U-Net-based semantic segmentation was first used for bio-medical purposes to detect disease using image segmentation and the obtained results were proven to be good (Ronneberger et al. 2015). The workflow architecture contains two paths where the image is considered as the input, and the identified object is obtained as the output. Firstly, the input path is used to consider the context of the image and is known as the encoder. The encoder pooling, ordering, and convolution stacking of the image layers following the output decoder path provide a symmetrical expanding path, which is used to provide exact localization using transposed 2-dimensional convolutions. Its process is an example of a full convolution network (FCN). The U-Net model will be extended through 3D U-Net model for volumetric segmentation with basic modification (Çiçek et al. 2016), and it may have enhancements for solving real problems of the earth. The present study used U-Net model for mapping two different species of trees in two unrestricted sites in India. The study demonstrates the (1) Object-based identification using images (aerial photographs), (2) Object identification with pixel-level accuracy, and (3) Mapping capability of the object.

18.3 Methodology

Aerial photographs of high spatial resolution, 0.5 m obtained from Microsoft Bing was used for the mapping and identification of (1) Coconut trees, and (2) Mango trees. The aerial photographs were for different non-restricted sites of India. The ERDAS Imagine version 2020 software was used for the deep learning semantic segmentation model, which is based on the U-Net workflow. The semantic segmentation deep learning object classification method consists of two parts: (1) Training, and (2) Testing of model (Fig. 18.2).

150 image chips and class label chips of 256 × 256 pixels for both coconut and mango trees were created. The model parameter epochs (Table 18.1) are the iteration by which the model learns from the object chips. The time of training the model increases with an increase in the number of provided epochs, and consequently, the training efficiency increases. The rate of learning parameter is expressed by a value that lies between zero to one. It has been observed that the smallest value is best suited for training the semantic segmentation model. For this study, 0.001 value was used. The learning and validation accuracy of the model is judged by itself. Learning accuracy refers to the value corresponding to the learning of chips by the model without any error, and greater the value, better the model. The validation accuracy is checked by the chips which aren't used for training the model (80% chips are used for training the model, and the rest 20% are used for testing and validating the model), to ensure the independent validation of the model.

The U-Net workflow provides an understanding about how the testing data is used as input to train the model to get the object-identified image as the output

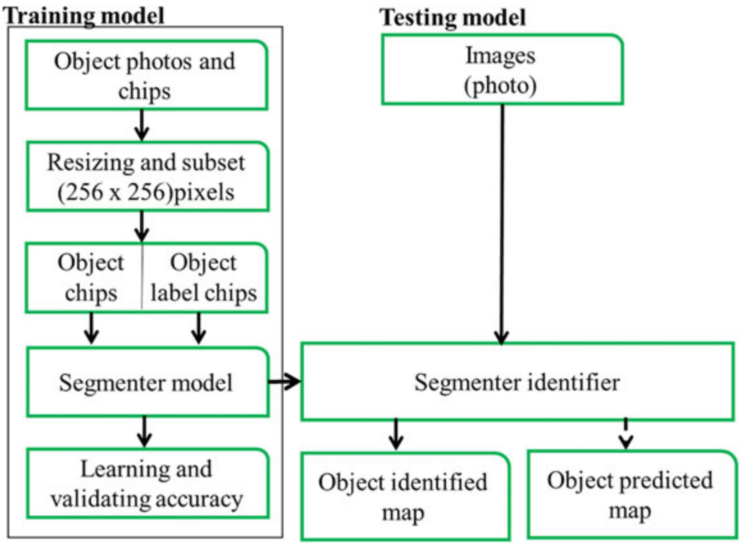

Fig. 18.2 Deep learning semantic segmentation model workflow for object identification

Table 18.1 Semantic segmentation deep learning model parameters and its values

S. no.	Semantic segmentation model parameters	Parameters value
1.	Epochs (iteration)	20
2.	Learning rate	0.001
3.	Validation percentage	20%
4.	Data directory	Path of data directory
5.	Output model intellect	Name and path of model intellect
6.	Learning accuracy	Model learning accuracy
7.	Validation accuracy	Model validation accuracy

(Fig. 18.3). The testing photo was provided as an input from upper left path for contraction, which follows the convolutional process. The convolution process increases the depth of the photos. The path down red arrow follows the maximum pooling process, in which photo is downsized up to half its size and the process is repeated up to number of epochs. It takes the photo data to the lowest part and builds two convolutional layers, without any further pooling. The photo is resized to its smallest and starts moving upward on to the right-up expansive path. The object label image is upsized to its actual extent and size on the expansive path with the use of an up-sampling method named, transposed convolution, which manages to expand the object identified image. The last layer, convolution layer is an image of the same and actual size, which is the object identified image.

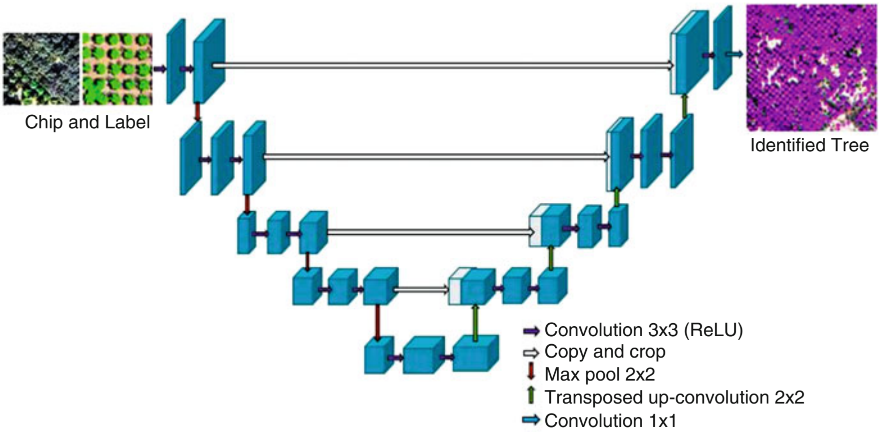

Fig. 18.3 U-Net architecture. The model comprises an encoder and a decoder pathway, with skip connections between the corresponding layers

Table 18.2 Validation and accuracy assessment of semantic segmentation deep learning method for object coconut and mango trees

S. no.	Tree type	Validation and accuracy assessment	Results (%)
1.	Coconut	Learning accuracy	94.2
2.		Validating accuracy	90.4
3.		Ground validation	82.0
4.		Tree canopy area validation	78.2
1.	Mango	Learning accuracy	93.9
2.		Validating accuracy	90.0
3.		Ground validation	81.6
4.		Tree canopy area validation	80.4

18.4 Results

The tree object is identified, mapped through the demarcation of pixels into a class group. The semantic segmentation deep learning method was used for the object identification of different trees, (1) Coconut, and (2) Mango trees of different locations. The ground-based validation was observed as the number of trees identified in the output result in the form of the mapped image and the number of trees counted in the region is presented as ground validation accuracy. The model mapping capacity for object tree canopy is also validated with object identified pixels, and manually demarcated tree canopy of both trees are represented by percentage value as the tree canopy area validation. The model learning and validation accuracy are represented in Table 18.2.

If the value of the model learning accuracy is higher than 95%, it is considered that the model's learning of the given chips is excellent. If it is in the range of

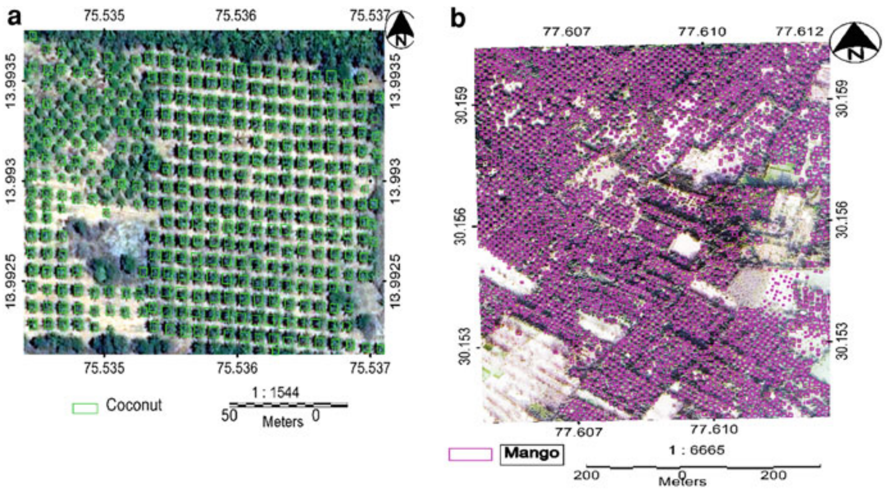

Fig. 18.4 (**a**) The object identified map of the coconut trees and (**b**) mango trees

90–95%, the model's learning is considered to be very good, and if it is in the range of 80–90%, the model's learning is considered to be satisfactory. The model needs to be run again with necessary corrections if the learning accuracy is calculated to be below 75%. The learning accuracy of a model represents the learning capacity reached by the model on a given dataset, and it can influence the validation, and ground validation accuracy. The higher the value of the validating accuracy, the better the model. However, a model is acceptable if the validating accuracy is above 75%.

The coconut and mango trees' (80%) chips were given for the learning and the learning rate shows the model successfully learned both tree models. The learning rate for both the tree models is above 94%, and model learnt perfectly with the given testing photo chips. The model itself validates its accuracy by using the rest of the training chips (20%) to provide a snap of output accuracy using photo chips. It also helps in understanding the testing accuracy and whether the model can be considered for testing other sets of image for object identification. The validation accuracy for both tree testing models is above 90%, and it is considered as good and acceptable. Further validation of the object identified output image was done by using the census of the identified tree against the census counting value obtained from the ground. The ground validation of both the trees, was good, with 82% and 81.6% for coconut and mango trees, respectively. The validation for tree canopy cover for coconut and mango trees is 78.2% and 80.4%, respectively (Fig. 18.4a, b).

18.5 Discussion

The object detection image can be of any size and scope, and it is utilized as the input image for testing the semantic segmentation model. The type, bits, and the number of layers of the training and testing image chips on which the model intelligence is built must be the same. The tree object is detected and mapped into a class group via pixel demarcation. The recognized pixels that cover more than 40% of the canopy cover are evaluated for a tree identification class as well as ground confirmation. Images with a higher spatial resolution (0.5 m) yield better results for tree identification. The semantic segmentation model accuracy and performance can be improved using images with high spatial resolution, more spectral layers(Geng et al. 2014), and images with a higher signal to noise ratio (Singh et al. 2016).

Microsoft Bing aerial photographs with a spatial resolution of less than 1 m were obtained for coconut and mango trees in various locations. The deep learning segmentation method was evaluated for tree identification using canopy pictures. For training the model, training image chips and class labels of comparable size and extent were generated. The semantic segmentation deep learning model is built and used to assess the given input pictures, which are similar in terms of kind, bits, and number of layers. An image of any size or scope can be used to identify both coconut and mango trees. The trained model is used to automate tree identification.

The classification methods which are based on pixel values, such as, Supervised Spectral Distance, Bayes and Maximum Likelihood method, need to provide the training signature file in order to obtain a classified map as the output image. However, it does not identify the type of tree, and hence, cannot be utilized for any census purpose. The unsupervised method of classification clusters the image pixels on the basis of calculated mean, variance, standard deviation, but it does not provide any information about the class and does not identify the tree. The hyperspectral image classification functions like the supervised classification method can identify the species of a tree, but it fails to retain shape in an area where the trees are clustered. It also fails to conduct the census of a tree. Since the processing is based only on spectral values the automatization becomes very difficult. Furthermore, the time required for processing is high and that poses a major challenge. The other object-based classification methods work on defined workflow from raster-based classification, object probability, operator-based cleaning, raster to vector conversion, operator-based shape retention. The whole workflow of the object-based classification method need to be processed every single time, and many modifications are required to be done at each stage to attain a good level of accuracy. Therefore, the processing of a large volume of data takes a considerable amount of time.

The machine learning techniques, Classification using Regression Tree (CART), Random Forest (RF), Support Vector Machine (SVM), Naïve Bayes (NB), Logistic Regression (LR) also work on the principle of supervised classification. The machine learning model trains its models based on feature vectors, chips, statistical values of the class. The model is used for classification, but it also fails to retain the shape of the object class. The deep learning segmentation method trains the model using object shape, pixel values, structure, texture to identify the tree class. It is also utilized for the automatization of tree identification processes (Majeed et al. 2020).

Despite numerous breakthrough advancements in deep learning algorithms for image and computer vision, a fundamental disadvantage of the technology is that it requires a vast number of training chips and data, which is almost impossible to feed at all times. All the training chips are of the same size, layer, and extent, often in multiples of 256 × 256 pixels; however, the amount of time required for training is determined by the number of training chips. For the semantic segmentation technique, each related chip snapshot must have its own object class. It performs better when the object class is provided together with a non-required back class for object-based identification.

18.6 Conclusion

The CNN-based methods have solved various complex problems with a good acceptable level of accuracy in the field of computer vision and imagery analysis. It opens up space for the other fields to adopt object-based identification for solving problems by using image-based analysis. We presented the semantic segmentation deep learning method for the identification of trees based using photos of their canopy. The semantic segmentation models identify objects with pixel-level accuracy, and it is useful to map the object since it accurately separates it from other objects in the background. It provides meaningful information about the object along with its identification.

The semantic segmentation deep learning method identifies the objects and is useful for the mapping of the object. It will also be used for automatization of the method using the same intellect model to test results on new datasets and images of other regions. It is very useful for faster identification, census, and mapping of trees. It is useful for finding the changes in the forest tree inventory, productivity, changes due to natural calamities and disasters. The method can find utility in forestry, for faster decision-making, efficient mapping of fire-affected areas, mapping invasive and threatened species, and better forest management. The method can be used for planning and monitoring forest and non-forested areas.

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Application of Biophysical, Soil, and Vegetation Indices to Better Understand Forest Dynamics and Develop Strategies for Forest Conservation

19

N. Mohan Reddy, Ishtiyak Ahmad Peerzada, Mohammad Moonis, and Ombir Singh

Abstract

The ever-evolving concept of conserving and sustainably managing the forests are some of the strategies being proposed for mitigating climate change. Monitoring, evaluation, and verification of forest conservation and management interventions are key issues that require to be addressed first to track its role in reducing climate change. The present state of forest management and monitoring in developing countries has limited scope for sustainable management and conservation. Here we present a range of biophysical and vegetation indices which can be assessed through remote sensing spectral imaging techniques. These indicators were tested at a landscape level to assess vegetation cover, primary productivity-to-soil properties, forest productivity, and consequently, forest health parameters using remote sensing-derived indicators, such as through Soil Adjusted Vegetation Index (SAVI), Red Edge Inflection Point (REIP), Brightness Index (BI) and Color Index (CI). These indices make it possible to periodically evaluate forest health with the help of spectral indices. With the advancement of satellite platforms and analytics of periodic spatial information, reliable and verifiable results can be produced from these indicators. However, these indicators are used at a limited level in forest management practices and, therefore, have not been exploited to their full potential. Although these indices

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vary with different spectral combinations, resolutions, platforms, and instrumentations, etc., they can provide qualitative as well as quantitative periodic information, which can be instrumental in planning and monitoring different forest management operations.

Keywords

Forest degradation · Forest monitoring · Forest management · Satellite imagery · Monitoring and evaluation · Spectral imagery · Remote sensing

19.1 Introduction

Anthropogenic-induced disturbances majorly shape forest landscapes in the subcontinent and play a major role in forest dynamics and the functioning of forest ecosystem services. In a developing country like India, forest management is a delicate balance between conserving and allowing the extraction of forest resources by the local communities within specific threshold of the ecosystem. Hence, it requires a robust information system on forest dynamics, ecosystem services, and their status, which are generally covered under national and subnational inventories. Further, periodic assessment of forest health and dynamics is a complex and resource-intensive process. The primary challenge in the assessment of the forest biophysical state is, therefore, the limited ability to compare different forest conditions quantitatively across ecological zones at frequent time scales (Tucker et al. 2008). Further, no standard methods are available and universally accepted for identifying the broad range of anthropogenic pressures and degradation processes (Reddy et al. 2021).

The application of biophysical and vegetation indices will help in integrated planning and conservation interventions to address emerging challenges like forest degradation (Neely et al. 2009). Notably, most management decisions have been done either on canopy cover or stand density without any consideration for the various ecosystem functions (Ranjan et al. 2016; Qazi et al. 2017). Further, these long-term management plans do not consider changing the forest dynamics due to abiotic and biotic factors. However, it is important to consider these unusual disturbances while planning various activities, such as forest fire management, on a regular basis. Further, these indicators complement ground-based inventories with remote sensing data for greater area coverage and to reduce the cost burden.

Remote sensing imagery technique makes it possible to make adaptive management decisions with the help of spectral indices, periodicity, the annual curve of spectral vegetation indices on productivity and seasonality, etc. The Revised National Working Plan Code, 2014, has recognized the potential of the remote sensing technique (Singh et al. 2014). However, the Working Plan does not prescribe biophysical indicators such as soil, vegetation cover, vegetation stress, and other indicators to assess forest health and ecosystem services.

The assessment and monitoring of the forest dynamics and health through remote sensing technique offers a series of following advantages: (a) it represents a consistent, coherent, transparent, and fairly accurate way of reporting on the area affected, and allows for near-real-time reporting on forest health; (b) it offers spatially explicit national data in remote and inaccessible regions; and (c) it is the only approach that offers objective information on historical trends in areas where data does not exist (Herold et al. 2011).

In the view of the aforementioned arguments, a range of remote sensing indicators has been presented here for the assessment of forest health which can help in deriving strategies for effective forest management. The objective of the paper is to present biophysical and vegetation indices derived from remote sensing data that can be used in forest management/planning.

19.2 Material and Methods

19.2.1 Study Area

The study was conducted in selected forest ranges of Itarsi and Sukhtawa of the Hoshangabad forest circle, Madhya Pradesh, India (Fig. 19.1) to demonstrate various remote sensing indicators. The study area has tropical dry-mixed deciduous forests, dominated by species like *Tectona grandis*, with patches of open scrub forests (Champion and Seth 1968). Tropical deciduous forests are the dominant forest type in India and cover more than 28.27% of its geographic area (FSI 2019).

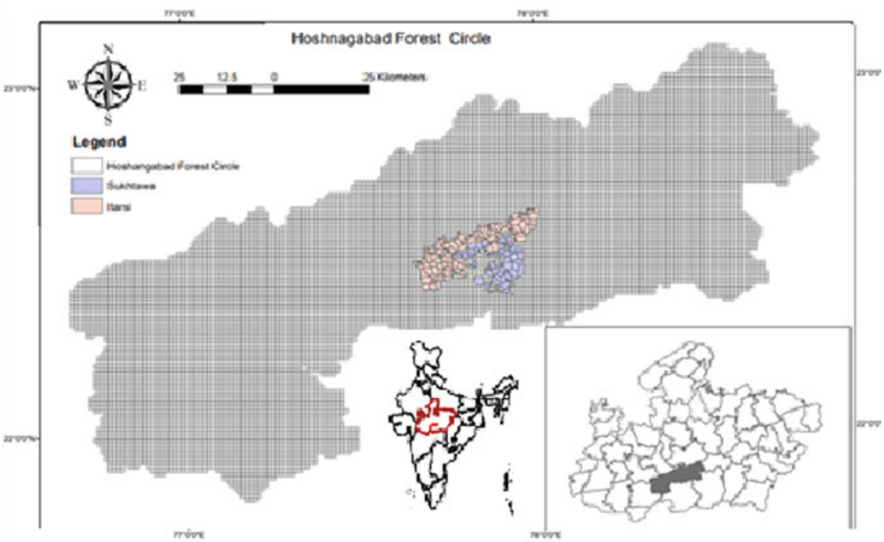

Fig. 19.1 Location of the study area (Source: FSI 2019 and Reddy et al. 2021)

The study area is located between 21 54′18″ and 22 38′50″ North latitudes, 77 46′7″ and 77 43′44″ East longitudes. The annual temperature of the area ranges from 20.5 to 25 °C and the average annual rainfall varies from 800 to 1800 mm.

19.2.2 Methods

This study used freely available Sentinel 2a remote sensing data (10 m × 10 m) images of the study area from Sentinel Scientific Hub from 2016, 2018, and 2020 (ESA 2016). Data like atmospheric and terrain correction and calculation of biophysical, soil, and vegetation radiometric indices were preprocessed using the Sentinel Application Platform (SNAP) Tool Box v7.0 (ESA 2017) and ArcGIS 10.4 (ESRI, California). In addition to the satellite data, field inventory data from 48 sample plots were collected (Fig. 19.2) using a grid-based sample design framework. Further, Google Earth was used to validate various biophysical, soil, and vegetation indices from the satellite data products.

Vegetation indices that are sensitive to photosynthesis were deduced from the combination of red and infrared spectral reflectance bands (Bannari et al. 1995). Sentinel offers a wide range of Infrared (IR) bands capturing a wide range of indices. In this study, three vegetation indices were used: SAVI, REIP, and Pigment Specific Simple Ratio (chlorophyll index) or PSS. The study also used three biophysical indices: Leaf Area Index (LAI), Canopy Water Content (CWC) and Fraction

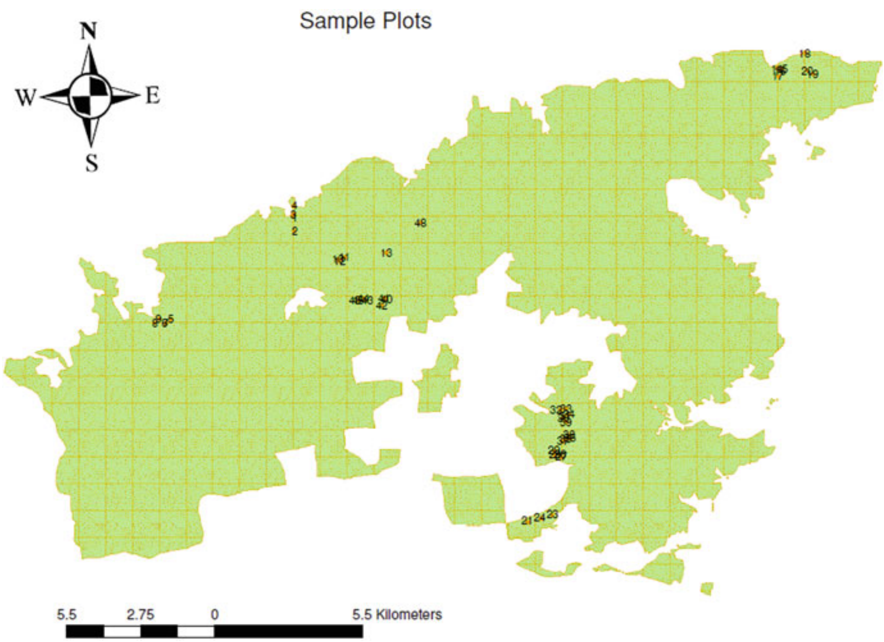

Fig. 19.2 Sample point locations at the study area

Vegetation Cover (FVC), and Soil Radiometric Index. CI and BI were calculated from the Sentinel-2A (Table 19.1).

19.3 Results and Discussion

19.3.1 Soil Adjusted Vegetation Index (SAVI)

Forest canopy cover or forest cover is defined as the proportion of forest area covered with tree crowns (Jennings et al. 1999). It is an important indicator of forest health and can demonstrate both deforestation as well as degradation. Further, it is a multipurpose ecosystem indicator for distinguishing between different plants and understanding canopy gaps. Canopy cover is commonly measured through remote sensing-based vegetation indices such as NDVI. However, for this study, the SAVI index was used for the detailed capture of the very sparse and sparse canopy cover after removing the influence of soil reflectance on the vegetation indices.

The recent advancement in remote sensing sensors such as the Sentinel-2 satellites has created a new opportunity for vegetation stress monitoring at refined spatial resolution (10 and 20 m). Further, the SAVI parameter is quite helpful in understanding the canopy cover in the fragment forests and developing future strategies to improve the ratings of the indicator. Likewise, the higher number of grids are still in the poor category, indicating tremendous scope for initiating landscape restoration activities and for sequestering carbon dioxide to meet the national emission targets such as Nationally Determined Contributions (NDCs) (Hof et al. 2017). The SAVI index varied between 0.86 and 0.01 across the study area. Further, this index was divided into ten classes as shown in Fig. 19.3.

19.3.2 Red Edge Inflection Point (REIP)

REIP is a remote sensing indicator of vegetation stress that depends on the amount of chlorophyll seen by the remote sensor (Dawson and Curran 1998). Red edge—the point of strong red absorption—indicates the information on plant nitrogen and growth status. The REIP general formula is based on the linear four-point interpolation technique and uses four wavebands, i.e., 670, 700, 740, and 780 nm (Baret et al. 1988).

The REIP index includes measurement of reflectance in the NIR and shortwave infrared radiation. For calculating this index, SNAP Tool software and Sentinel 2A data were used. Based on the relative weightage of the class and corresponding area, the relative importance was calculated and categorized into ten categories (Fig. 19.4). The areas with very high REIP values need to be improved in terms of protection and reduction of biotic pressure. Buffer area management is very important for the high biotic pressure areas.

Table 19.1 Formulae for biophysical and vegetation indices

Indices	Formulae to calculate the indices
Vegetation indices	
SAVI (Huete 1988)	SAVI = [(NIR − red)/(NIR + red + L)] × (1 + L), where NIR is near infrared reflectance, Red is red reflectance, and L is the correction factor
REIP as an indicator for vegetation stress (Frampton et al. 2013)	REIP = 700 + 40 × [(red1_factor × red1 + IR_factor×near_IR)/2) − red2_factor ×red2) / (red3_factor × red3 − red2_factor × red2)] For Sentinel-2 (Sentinel-2 bands are at 705 and 740 nm) the formula is provided 705 + 35 × ([B4 + B7]/2 − B5)/(B6 − B5), where (central wavelength/bandwidth): B7 = 783 nm (15 nm), B6 = 740 nm (15 nm), B5 = 705 nm (15 nm), B4 = 665 nm (30 nm)
PSSRa (chlorophyll index) (Blackburn 1998)	Using Sentinal-2 data, PSSRa = $\rho_{783}/\rho_{665;}$ ρ_{800} and ρ_{680} reflectances at 783 and 665 nm, respectively
Biophysical indices	
LAI (Wang et al. 2007)	LAI = $\rho_n - \rho_r/\rho_n + \rho_r$ Where LAI is the leaf area index, ρ_n is the reflectance in Redwaveband, and ρ_n is the reflectance in NIR waveband
CWC (Yebra et al. 2013)	Canopy water index = $(\rho_{857} - \rho_{1241})/(\rho_{857} - \rho_{1241})$, Where ρ_{857} is reflectance at 857 nm and ρ_{1241} is reflectance at 1241 nm
FVC (Caloz et al. 1988)	FVC = [(NDVI – NDVIsoil)/(NDVIveg – NDVIsoil)] Where NDVI = normalized differential vegetation index (with and without soil) FVC estimation is combination of Band 4 Red (665 nm), Band 12 SWIR2 (2190 nm) and Band 8a NIR2 (865 nm)
Soil radiometric indices	
CI (Vodyanitskii et al. 2007)	CI = (red_factor * red − green_factor * green)/(red_factor * red + green_factor * green)
BI (Pałaś and Zawadzki 2020)	BI = sqrt (red factor * red * red_factor * red) + (green_factor * green * green_factor * green)/2)

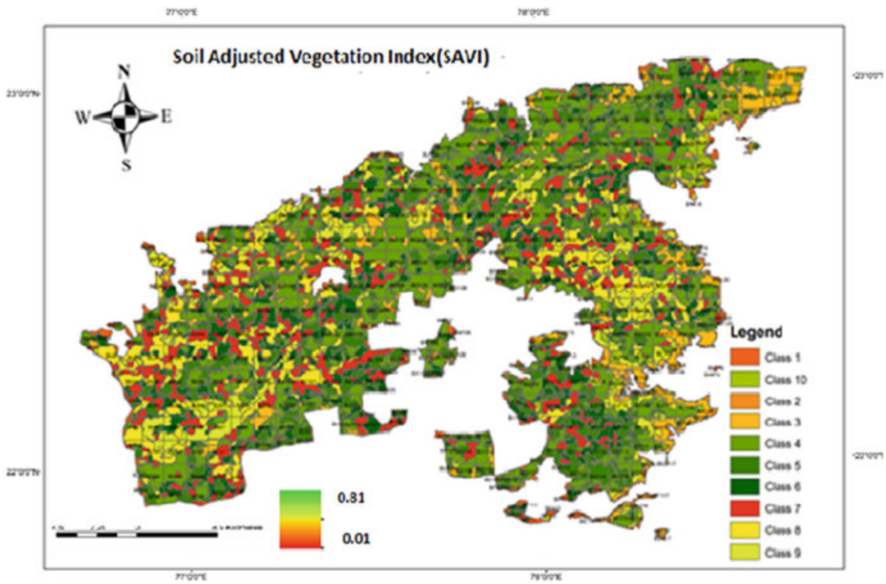

Fig. 19.3 Map showing the canopy cover using SAVI index

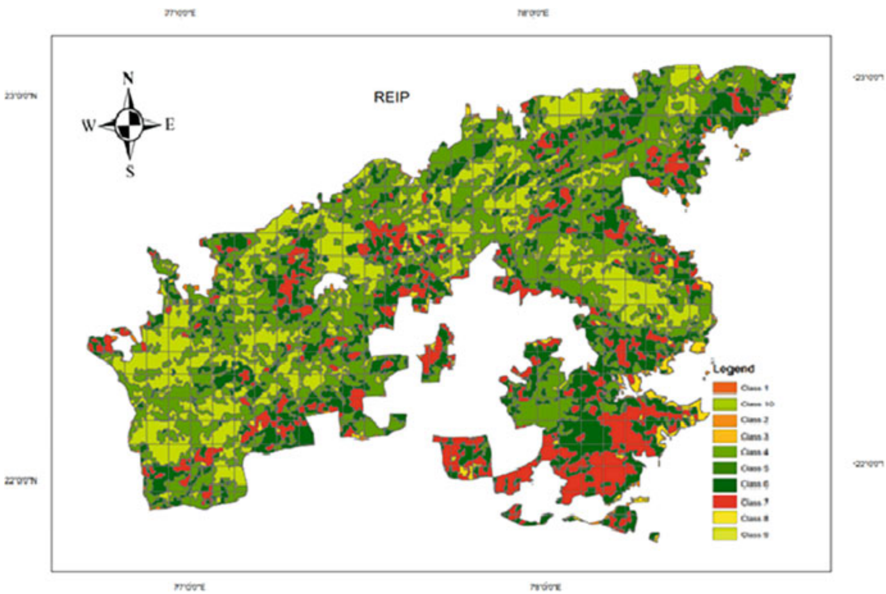

Fig. 19.4 Map showing REIP values across the forest landscape

19.3.3 Pigment Specific Simple Ratio for Chlorophyll a (PSSRa)

Spectral vegetation indices such as NDVI are being widely used for biomass estimations and have shown correlation to biomass accumulations. However, these indices are now being used only for biomass estimations instead of being utilized to their full potential in monitoring forest health status. It is also important to understand crucial factors like chlorophyll content and its efficiency, which are directly influenced by various natural stressors and anthropogenic disturbances. Timely and accurate canopy chlorophyll monitoring helps in successful management interventions on a periodic basis. Their performance to changes in illumination conditions, soil background, water availability, etc. provides an important basis for executing and evaluating forest management activities.

PSSRa is a simple ratio 800/675 nm band of the Sentinel 2-A, which denotes the active chlorophyll content of the vegetation (Caasi et al. 2020). PSSRa provides a better interpretation of the forest biomass across the landscape and also adds information on the chlorophyll content variations across the different parcels (Fig. 19.5). This index captures the concentrations of photosynthetic pigments, biophysical attributes, and spectral reflectance characteristics of the structurally complex, heterogeneous canopies of dry deciduous forests. Hence, it is more accurate in biomass estimation than other vegetation indices like NDVI and SAVI. This index value also correlates to NTFP production apart from forest biomass. Overall, the study area was classified into 10 forest carbon stock strata for the analysis using the ARCGIS 10.4 (ESRI, California).

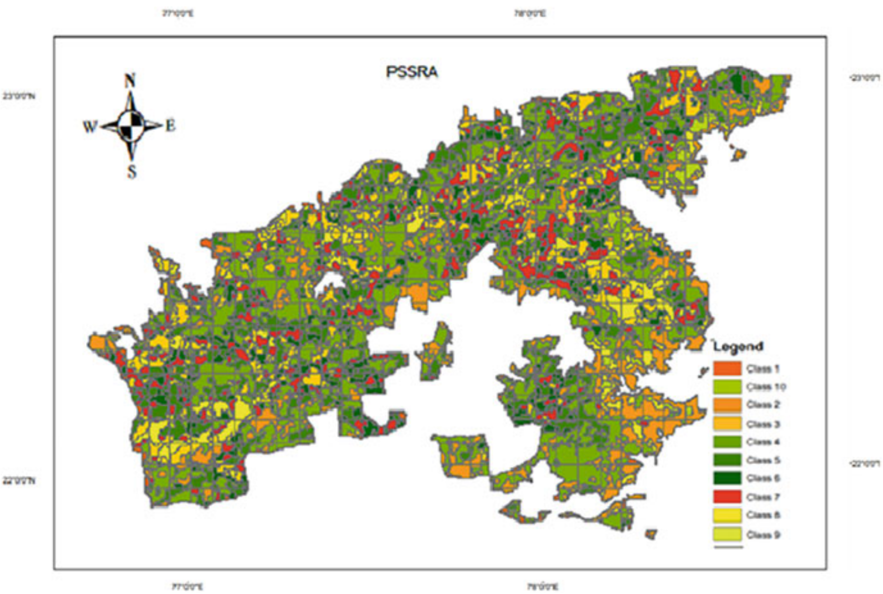

Fig. 19.5 Map showing PSSRa

Biomass estimations from the 46 sample quadrates provided an overview of the natural variation carbon stocks. For the inventory, trees with a minimum diameter of 10 cm at breast height (DBH) were collected in the 0.1 ha sample plots and extrapolated. The biomass calculation was based on allometric equations as proposed by Intergovernmental Panel on Climate Change (IPCC) (Penman et al. 2003). Overall, “very good” category forests reported more than 170 tons ha^{-1} of forest carbon stock, whereas “degraded” forests reported less than 30 tons/ha. It is evident from the PSSRa values that less than 20% forest grid reported good forest carbon stocks. There is an inherent potential from the forest area to sequester more carbon with appropriate management interventions. This indicator also supports reporting on carbon stocks from the stand to the national level. The biomass varies from 11.01 tons $ha^{-1}$to 396.36 tons ha^{-1}at the study site. This data was further used to understand the PSSRa vegetation index classification purposes. Further, these index values were divided into 10 classes/strata, as shown in Fig. 19.5.

PSSRa provided a better interpretation of the forest health across the landscape and also added information on the biomass variations across the different parcels. Overall, the study area was classified into ten forest carbon stock stratums for the analysis using this index. The areas categorized under lower PSSRa can be visited to take up conservation activities.

19.3.4 Fractional Vegetation Cover (FVC)

Recurrent biotic pressures cause fragmentation of the forest parcels areas where a kind of “edge effect” can be observed on the forest/non-forest boundaries with a devastating effect on both flora and fauna. Further, this fragmentation reduces the forest canopy cover to a level where it creates unviable patches of forest fragments, causing adverse impacts on the corridor connectivity, which is one of the important criteria for landscape sustainability. Fractional Vegetation Cover (FVC) is a biophysical indicator that provides detailed information on the fragmentation, which can be used to make management plans to address this issue (Cai et al. 2020).

In general, FVC reflects the size of the plant photosynthetic area and the density of vegetation growth because of anthropogenic activities. The FVC index varied between 0.77 and 0.02 across the study area (Fig. 19.6). Further, this index was divided into ten classes to plan the conservation activities. The areas with lower FVC values need protection and gap planting to reduce fragmentation. Similarly, areas with higher FVC need to be protected from biotic interferences.

19.3.5 Canopy Water Content (CWC)

Remote sensing technologies are widely used for assessing fire data and forest cover monitoring (Babu et al. 2016). This study has used CWC as a proxy remote sensing variable for the forest fire potential (Reddy et al. 2021). This indicator explains the amount of water contained in vegetation foliage. It is based on the positive

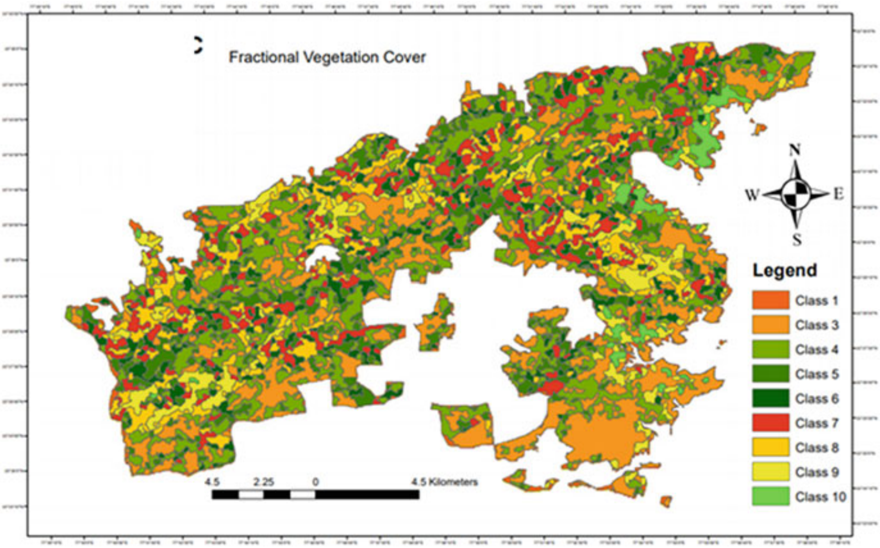

Fig. 19.6 Map showing FVC for the study area

relationship between higher canopy water content and healthier vegetation, which is fire resistant in general (Danson and Bowyer 2004; Quan et al. 2015). Further, CWC can explain other ecosystem health indicators, as the sufficient supply of moisture ensures higher photosynthesis processes. Dry deciduous forests are more susceptible to forest fires, which subsequently trigger degradation processes.

The CWC index includes measurement of reflectance in the NIR and shortwave infrared radiation. For calculating this index, SNAP Tool software and Sentinel 2A data were used. The CWC index varied between 0.07 and 0.001 across the study area. Further, this index was divided into ten classes as shown in the Fig. 19.7. The region with lower CWC values can be prioritized by forest managers to plan the development of fire breakers, changes in species compositions, soil water conservation work, etc.

19.3.6 Leaf Area Index (LAI)

In general, net primary production (NPP) is the proportion at which the total autotrophs in an ecosystem generate the net useful chemical energy. The direct estimation of the NPP is a complicated process. However, LAI is a proxy remote sensing indicator that can be used for the estimation of the NPP (Darvishzadeh et al. 2019). In this study, LAI is considered as indirect indicator of the NPP.

LAI denotes the leaf surface area per unit area, which ranges from 0 (bare ground) to 10 (dense forest). It provides important information on the forest's structure, function, and capacity to provide services and goods. It performs better than other

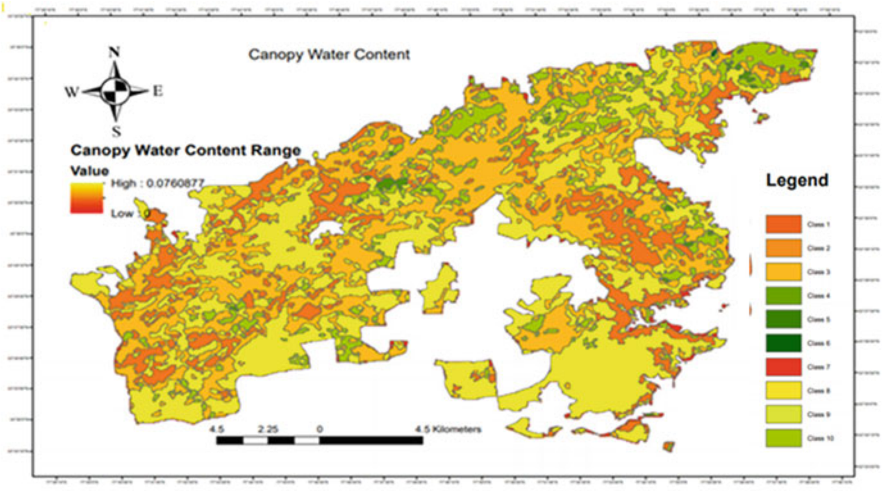

Fig. 19.7 Map showing CWC

widely used vegetation and biophysical indexes (e.g., NDVI, FVC, and enhanced vegetation index). Further, the temporal measurements facilitate consideration of the structural changes, which is not necessarily observable with spectral indices. Sentinel 2A data and SNAP Toolbox were used to calculate the LAI for the study area. The LAI supports estimation of photosynthetic primary production, evapotranspiration, and as a reference tool for crop growth. The LAI value varies from 3.44 to 0.07 across the landscape. The LAI rates of >3 can be considered to be very good for the production function of flowering/fruiting and biomass accumulation. So, this indicator can be used to simulate the production of NTFPs to prepare management plans for the NTFPs. So far, field-based sampling methods are being employed to study the NTFP yields. Overall, a significant portion of the study area shows low LAI rates due to biotic pressure, which denotes the potential to recoup any temporary disturbances. Therefore, the framework is sensitive towards the restoration potential of the forest areas.

A lower value suggests the requirement of conservation efforts in these areas (Fig. 19.8).

19.3.7 Soil Organic Carbon (SOC)

Understanding the soil nutrient content is important to sustain the quality of forest soil and to maintain support to the forest floor and belowground ecosystem (Bhattacharyya et al. 2007). Soil nutrient content plays an important role in the overall forest growth and provides the essential moisture and nutrients for tree growth. In general, it can be reflected as a percent of soil organic carbon or biomass production. For this study, soil organic content was selected as an indicator for

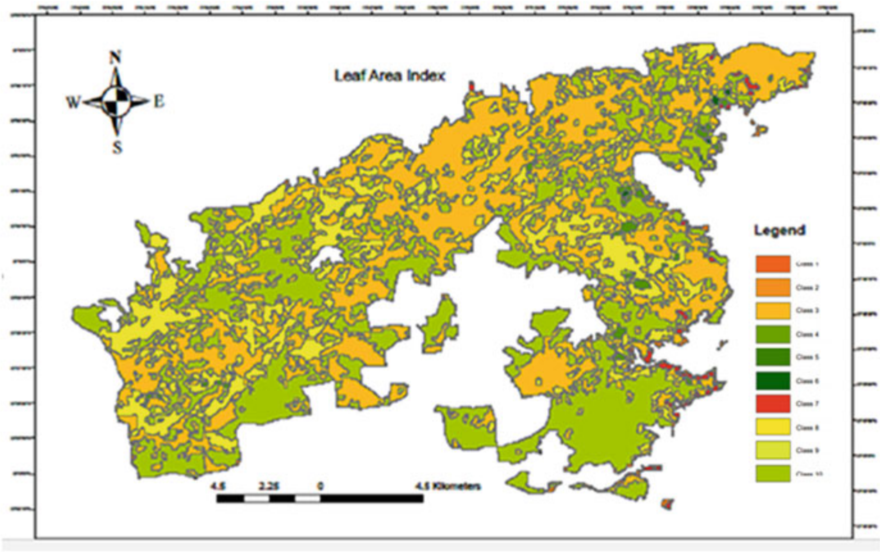

Fig. 19.8 Map showing LAI

understanding the forest dynamics. However, direct measurement of SOC is time-consuming and expensive (Ritchie et al. 2007). Further, the direct measurement can be prone to error due to sampling and handling of samples.

Soil color can act as an effective proxy to measure the forest SOC (Viscarra Rossel et al. 2016). There is a positive relation between SOC and soil color because the amount of SOC in the soil also impacts the color and appearance of the soil (Wills et al. 2007). In the area of soil science, basic soil color measurement is done visually using the Munsell soil color chart (Pendleton and Nickerson 1951). However, measurement of soil color using Munsell chart has many drawbacks, such as limited number of colors to compare and its subjective nature of identification of soils purely on the basis of soil color (Gholizadeh et al. 2020).

With the advancement of GIS and remote sensing technology, SOC can be measured using visible and infrared wavelengths. These wavelengths can be transformed into color indices to measure SOC (Kumar et al. 2016). In this study, soil organic carbon was studied through remote sensing and field inventory data. The SOC values varied from 110 tons ha^{-1} to 5.72 tons ha^{-1} across the various sample plots (Fig. 19.9). Further, the CI data was calculated for the entire study area and grouped into 10 classes (Fig. 19.9). The lower CI correlated with the presence of high concentration of SOC and presence of higher carbonates or sulphates. In addition, these indices complement information with the BI and the NDVI.

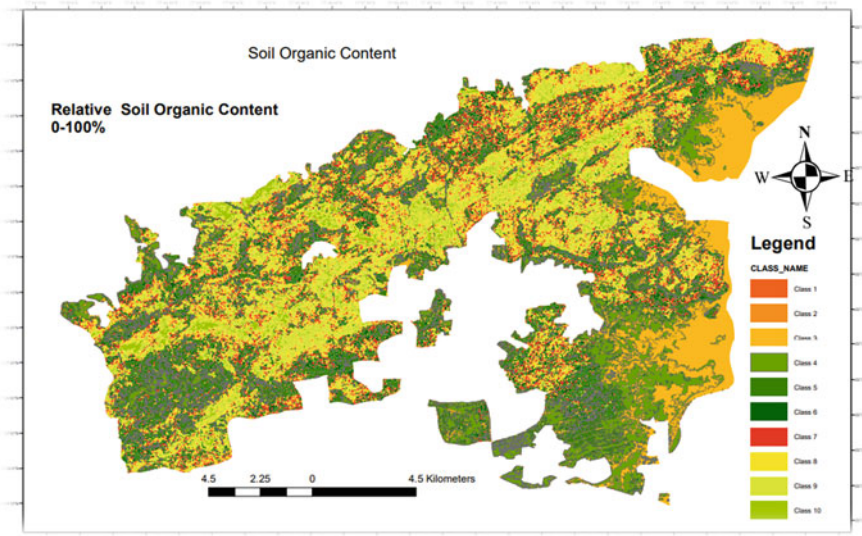

Fig. 19.9 Map showing soil organic carbon

19.3.8 Soil Moisture

Forest soil water retention is a complex function of soil moisture, soil depth, and bulk density, which also varies across the season (Venkatesh et al. 2011). Soil water enhances the stability of the forest ecosystem, regulates run-off, and supports the growth of plants. In semi-arid areas, forest soil water balance determines the forest growth, composition, and the overall ecosystem services. Remote sensing images provide soil moisture content of the entire landscape periodically and supports the conservation efforts to address forest droughts and water stress. The BI algorithm derived from the sentinel data provides the soil moisture variance across the landscape (Seuffert et al. 2004). The result is a panchromatic image and is sensitive to the brightness of soils. Sentinel 2A data and SNAP Toolbox software were used for calculating the BI. It varies from 0 to 1 in the study site. Based on the relative weightage of the class and corresponding area, the relative importance was calculated and categorized into ten groups (Fig. 19.10).

19.4 Conservation Planning

The study area was divided into systematic grids, and the composite index was deduced from the biophysical and vegetation indicators with different scales to provide the basis for comparing and conservation planning (Majasalmi et al. 2020). This index is sensitive to forest structure, ecosystem services, and improves modelling of successional dynamics (Table 19.2). Further, the composite index

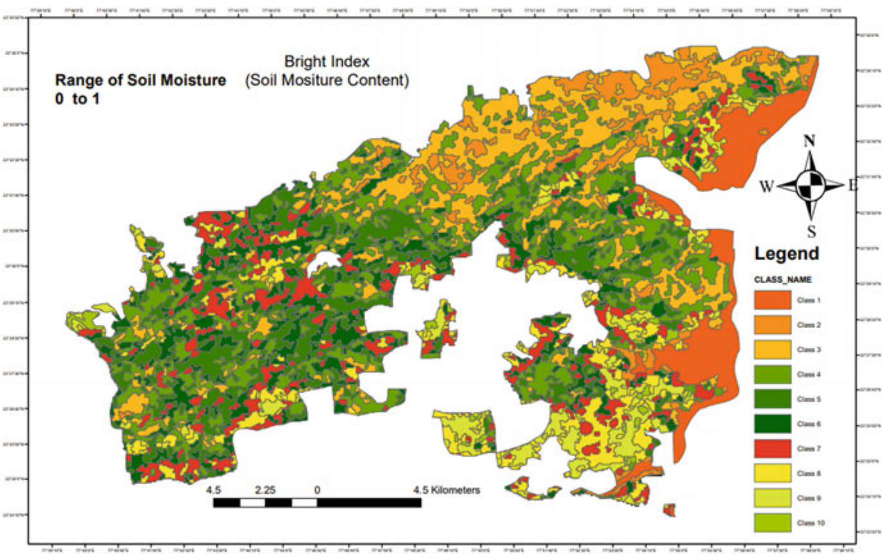

Fig. 19.10 Map showing soil moisture—BI

Table 19.2 Correlation coefficient significant

	SAVI	FVC	PSSRa	LAI	REIP	BI	CWC	CI
SAVI	1							
FVC	0.95*	1						
PSSRA	0.96*	0.99*	1					
LAI	0.61*	0.50*	0.51*	1				
REIP	0.85*	0.79*	0.81*	0.80*	1			
BI	0.90*	0.85*	0.88*	0.57*	0.84*	1		
CWC	0.64*	0.51*	0.55*	0.96*	0.86*	0.65*	1	
CI	0.74*	0.81*	0.57*	0.77*	0.59*	0.67*	0.71*	1

reduces subjective judgments and provides specific indicators to improve the rating of the forests, and sometimes the measurement outcomes become easy to interpret (Siry et al. 2005).

Further, Google Earth was used to validate the conservation planning using 50 random sample points from 20 sample grid to validate the results (Kappa coefficient > 90%). Based on the value of composite index, the study areas were divided into a Conservation Zone, Regeneration Zone, Protection Zone, Restoration Zone, and Extreme Restoration Zone. The planning can be further broken for individual zones based on the values of the indices (Fig. 19.11).

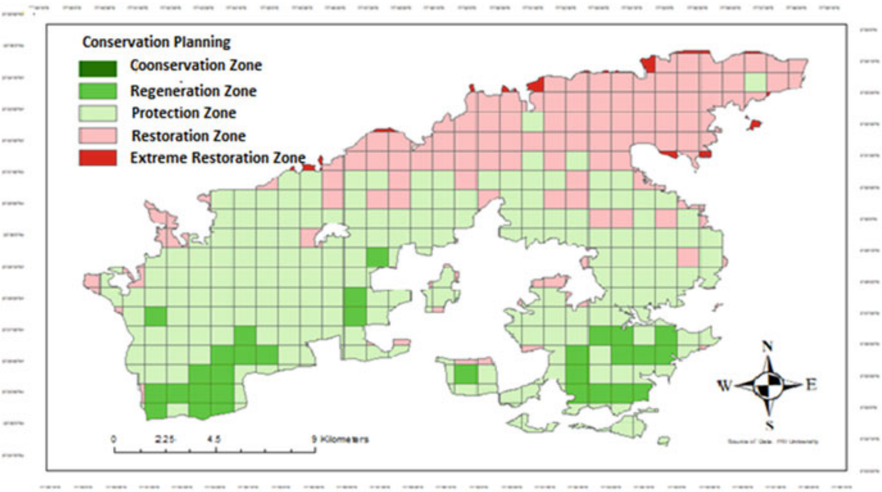

Fig. 19.11 Conservation planning

19.5 Synthesis

It is a challenge to effectively monitor, report, and verify the level of forest degradation and deforestation on spatial and temporal scales. Moreover, budget and resource constraints for the assessment of forest deforestation and degradation, which can vary according to site location and conditions, pose an additional challenge. Biophysical and vegetation indicators derived from remote sensing imaging techniques could be convenient to correctly map and monitor changes in key deforestation and degradation parameters. The present work presented and expanded the methodological framework for the integration and application of remote sensing techniques into the indicators of degradation and deforestation parameters like forest canopy cover, level of vegetation stress, plant productivity, vulnerability to dryness or drought, and soil organic carbon. These eight indicators developed from the remote sensing techniques can also be used to detect changes in the site-specific biophysical and vegetation features. By locating variations in the spectral properties, healthy and degraded, and deforested forest ecosystems can be differentiated from each other. The site-specific practical application has been demonstrated at the landscape level in a selected forest area of Central India. However, the implementation of these indicators is still in their infancy stage and have not been exploited to their full potential. Nonetheless, these indicators can provide qualitative and quantitative temporal and spatial data, which can be instrumental in planning, monitoring, and decision-making in the context of forest degradation and deforestation.

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Part IV

Advanced Institutional Provisions and Governance Framework

Emission Reductions Program for Addressing Drivers of Deforestation and Forest Degradation: An Insight from the Terai Arc Landscape in Southern Nepal

20

Shankar Adhikari and Himlal Baral

Abstract

As part of the REDD+ program, for the past decade, Nepal has been working with the World Bank's Forest Carbon Partnership Facility on its Emission Reductions Program (ER-Program). The ER-Program was designed for a program area covering 13 districts in the Terai Arc Landscape. Approved in 2018, the Emission Reductions Program Document (ERPD) identified six major drivers of deforestation and forest degradation in the program area: unsustainable and illegal harvesting of timber and fuelwood; overgrazing; forest fires; encroachment and conversion of forest land for other land uses; resettlement; and infrastructure development. The ER-Program aims to address these drivers and help the conservation and enhancement of existing forest carbon stock through the sustainable management of forest resources. To do so, seven program interventions have been designed, ranging from localized and improved community-based forest management, through private sector engagement in the forestry sector and alternative energy promotion, to integrated land-use planning. The February 2021 Emission Reductions Payment Agreement (ERPA) between the Government of Nepal and the World Bank has paved the way for official implementation of these interventions on the ground. These interventions unlock the potentiality of up to USD 45 million in results-based payments for emission reductions of up to nine million tons of carbon dioxide equivalent by 2025. Accordingly, the ER-Program is expected to address the drivers of emissions-causing deforestation and forest

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degradation and enhance forest carbon stock, ultimately paving the way for results-based payments for future emissions reductions.

Keywords

REDD+ · Emission reductions · Drivers · Deforestation · Forest degradation · Biodiversity · Forest restoration

20.1 Introduction

Forests provide a cost-effective means for climate mitigation as they sequester carbon dioxide, one of the major greenhouse gases (GHGs), preventing emissions into the atmosphere (Valatin and Price 2014; Funk et al. 2019). Therefore, forest-based emission reductions programs are considered low-hanging fruit in the debate on GHG emissions reductions (Hein et al. 2018). However, when forests are poorly managed, they become sources of emissions (Pearson et al. 2017). Forest-based emissions reductions programs are designed to address the drivers of deforestation and forest degradation, and conserve and enhance forest carbon stock (Bayrak and Marafa 2016).

Reducing Emissions from Deforestation and Forest Degradation (REDD+) is one of the major forest-based emission reductions (ER) programs focusing on the roles of conservation, sustainable management of forests, and enhancement of forest carbon stock in developing countries (Duchelle et al. 2019). The concept of REDD+ emerged during the 11th Conference of the Parties (COP 11) of the United Nations Framework Convention on Climate Change (UNFCCC) as Reducing Emissions from Deforestation (RED) (Pistorius 2012). It then evolved to become Reducing Emissions from Deforestation and Forest Degradation (REDD) at COP 13, and finally became REDD+ at COP 15 in 2009 (Corbera et al. 2010; Pistorius 2012; den Besten et al. 2014). REDD+ is therefore a policy instrument under the UNFCCC policy that is expected to tap into the large mitigation potential for conservation and better management of the world's forests through financial flows from developed to developing countries (Shrestha et al. 2014). It includes five activities, namely, reducing emission from deforestation, reducing emission from forest degradation, the Conservation, Sustainable Management of Forests, and Enhancement of Forest Carbon Stocks (den Besten et al. 2014).

The two main REDD+ multilateral initiatives in place are the World Bank's Forest Carbon Partnership Facility (FCPF) and the United Nations UN-REDD Program (Danon and Bettiati 2011; FCPF 2020). FCPF is a global partnership of governments, businesses, civil society, and indigenous peoples' organizations focused on REDD+. FCPF now works with 47 developing countries in Asia, Africa, Latin America, and the Caribbean, along with 17 donors with contributions and commitments totaling USD 1.3 billion (FCPF 2020). The UN-REDD Program is a collaborative program on REDD+, building on the convening role and technical expertise of the Food and Agriculture Organization of the United Nations, the United

Nations Development Program and the United Nations Environment Program. It supports nationally led REDD+ processes and promotes the informed and meaningful involvement of all stakeholders in national REDD+ readiness efforts in 65 partner countries spanning African, Asia-Pacific, and Latin American regions, including indigenous peoples and other forest-dependent communities, in national and international REDD+ implementation (Sanz 2016). A growing number of countries are engaged in both REDD+ forest-based emissions reductions initiatives (Danon and Bettiati 2011).

Nepal has been involved in forest-based emissions reductions programs since 2008 when a REDD Forestry and Climate Change Cell was established under the then Ministry of Forests and Soil Conservation (Dhungana et al. 2018). It is working with the World Bank's Forest Carbon Partnership Facility (FCPF), with an FCPF readiness grant supporting Nepal in implementing its REDD+ readiness program. Most of the Readiness activities under the readiness grant are concentrated in four areas: (1) readiness coordination and consultation with focus on capacity building activities; (2) National REDD+ Strategy Preparation; (3) formulation of reference scenario on emission levels and national forest monitoring system; and (4) project management activities. In the meantime, REDD+ pilot project on designing and setting up of governance and payment system for Nepal's community forest management under REDD+ was implemented from 2009–2013 in three watersheds (Charnawati in Dolakha, Kayarkhola in Chitwan, Ludikhola in Gorkha district) from three different geographic regions of Nepal. It covered more than 10,000 ha with 112 community forests, and users from 18,000 households with 90,000 people (Shrestha et al. 2014). Studies have shown that on average, carbon stock increased in forests under the REDD+ activities during the pilot project with increases in carbon stocks in forests for all altitudes and canopy types (Pandey et al. 2014a, b).

The ER-Program in Nepal was developed in accordance with the FCPF Carbon Fund Methodological Framework. The framework guides the development of ER programs and the selection of programs for the Carbon Fund portfolio (FCPF 2016). In 2018, following the Methodological Framework, the Government of Nepal prepared and approved the Emission Reductions Program Document (ERPD) (REDD IC 2018a), which was subsequently approved by the eighteenth meeting of the FCPF Carbon Fund in June that year. The ERPD is now the guiding document for Nepal's ER-Program. With the February 2021 Emission Reductions Payment Agreement (ERPA) between the Government of Nepal (GoN) and the World Bank, Nepal has now officially entered the ER-Program implementation phase. The GoN- and World Bank-approved ERPD forms the basis for ER-Program implementation under the REDD+ scheme. This ER-Program is being implemented in the lowland Terai region of the Terai Arc Landscape (TAL).

The TAL is a contiguous lowland region, which serves as the ER-Program area; an area of 2.4 million ha covering five provinces and 13 districts in southern Nepal. The program area represents the region of the country with the highest historical rates of deforestation and forest degradation (REDD IC 2018a).

Different drivers of deforestation and forest degradation have been discussed for the ER-Program area (REDD IC 2018a), and nationally (Acharya et al. 2011;

Chaudhary et al. 2016; REDD IC 2018b). Important drivers include forestland encroachment, infrastructure development, illegal harvesting of timber and fuelwood, and forest fires. In addition, limited financial and technological resources, and insufficient alternative livelihood opportunities, among others, are recognized as major barriers to addressing key drivers of deforestation and forest degradation effectively.

The ER-Program aims to address identified drivers of deforestation and forest degradation through the sustainable management of forests in the region. In doing so, it is also expected to support the conservation and enhancement of forest products and associated forest carbon stock (REDD IC 2018a). Nepal's National REDD+ Strategy also aims to reduce carbon emissions and enhance carbon stock and ecosystem resilience by minimizing the causes and effects of the drivers of deforestation and forest degradation, and promoting sustainable forest management across ecological regions (REDD IC 2018b).

In order to achieve its objectives, the ER-Program has designed seven areas of intervention. Program interventions were proposed around government priorities and regular activities in sustainable forest management, community-based forest management, livelihood improvement, alternative energy promotion, and overall economic development (REDD IC 2018a). Moreover, the ER-Program includes a set of strategic options and mitigation measures aimed at resolving drivers of deforestation and forest degradation, overcoming barriers in the current forest sector governance framework, and fostering a more sustainable and inclusive model. The ER-Program will involve public sector participation in each of these interventions and strengthen multi-sector coordination between various public entities and institutions. Public sector provisions in the ER-Program are justified given the global nature of many of its expected benefits, such as climate change mitigation and biodiversity conservation.

With its seven areas of intervention, ER-Program emission reductions are expected to reach 34.2 million tons of carbon dioxide equivalent ($MtCO_2e$) in the 10 years from 2018 to 2028 (REDD IC 2018a). As a result, the ER-Program aims to generate payments for verified emissions reductions relating to reduced deforestation and forest degradation and enhancement of forest carbon stock in the Terai Arc Landscape, with payments distributed in accordance with an agreed-upon Benefit Sharing Plan (REDD IC 2018a).

This paper discusses how the ER-Program helps address the drivers of deforestation and forest degradation in the Terai Arc Landscape in Southern Nepal to achieve set emission reductions targets.

20.2 Emission Reductions Program Area

The ER-Program area lies in the Terai Arc Landscape along the foothills of the Himalayas in the southernmost part of Nepal, known as the Terai region. The 2.4-million-ha program area is also jurisdictional, aligned with the 13 districts in five provinces of Nepal (Fig. 20.1). These districts include—from East to West—

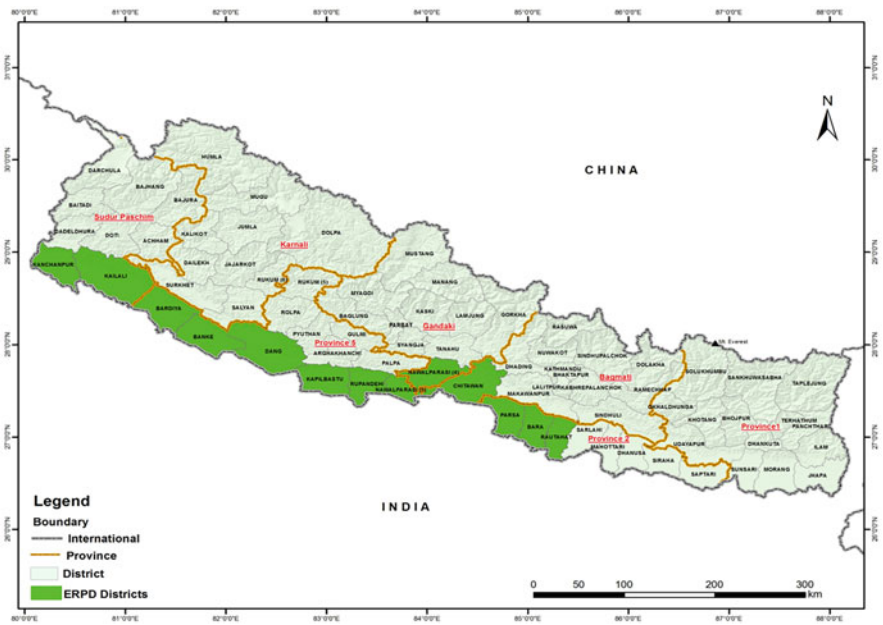

Fig. 20.1 ER-Program area in the 13 districts of the Terai Arc Landscape in southern Nepal

Madhesh Province (Rautahat, Bara, and Parsa); Bagmati Province (Chitwan); Gandaki Province (Nawalpur); Lumbini Province (Parasi, Rupandehi, Kapilbastu, Dang, Banke, and Bardiya); and Sudurpashchim Province (Kailali and Kanchanpur). It represents approximately 15% of Nepal's total land area, 20% of Nepal's national forest area, and 25% of Nepal's population. In 2013, around half of the TAL was under forest cover (1.17 million ha) (REDD IC 2018a). Of this, 29% (330,000 ha) was within protected areas and 24% (280,000 ha) under community forest. An additional 5% (60,000 ha) was collaborative forest; and the remaining 500,000 ha were predominantly government managed forest.

In addition, the ER-Program was built on the foundational successes of the first phase of the TAL Program for protecting forests, species, and ecosystems across the region while expanding sustainable livelihood opportunities for the people (MoFSC 2015).

The ER-program area is also rich for its cultural heritage due to the presence of various indigenous and ethnic communities. For example, Tharu community is one of the main indigenous communities that has been living in the region for generations. They have their cultural and traditional values associated with natural resources and forests contributing to the conservation and protection of the forests. Similarly, there are numerous other ethnic communities living in the area, including migrants from the Mid Hills and Himalaya regions. Overall, indigenous communities represent the largest segment of the population (31%), followed by High Caste Hill Groups (24%), Madhesis (23%), Dalits (12%), and Muslims (9%) in the region. The main source of income and means of livelihoods for the people are agriculture, animal husbandry, employment, and remittance (REDD IC 2018a).

20.3 Drivers of Deforestation and Forest Degradation

The ER-Program area has been facing anthropogenic pressures in recent years. Different studies have revealed a complex mix of interrelated drivers and underlying conditions, which form the basis for this section and the assessment of drivers of deforestation and forest degradation in Nepal, including in ER-Program area. The Terai Arc Landscape Strategy and Action Plan: 2015–2025, for instance, identified five drivers of deforestation and forest degradation. These include unsustainable and illegal harvesting of forest products; overgrazing; fuelwood collection; forest fires; conversion of forests to other land uses (encroachment, resettlement, infrastructure) (MoFSC 2015). It also identified a further four underlying causes: population growth, weak supply chain governance, increasing numbers of livestock, and increasing demand for forest products (MoFSC 2015; REDD IC 2018a).

Similarly, another study on understanding the drivers and causes of deforestation and forest degradation in Nepal and determining potential policies and measures for REDD+ identified seven drivers of deforestation and forest degradation (MoFSC 2014). These drivers were illegal logging, encroachment, fuelwood consumption, road construction, forest fires, mining, and grazing. The study also summarized some underlying causes, including poverty and high dependency on forests, increased demand for forest products, weak land tenure, weak governance and law enforcement, population growth, and political instability. Nepal's National REDD+ Strategy also summarized nine key drivers in the context of Nepal: unsustainable and illegal harvesting; forest fires; infrastructure development, including manmade disasters; overgrazing/uncontrolled grazing; weak forest management practices (unmanaged/undermanaged); urbanization and resettlement; encroachment; mining/excavation (sand, boulders, stones); and proliferation of invasive species (REDD IC 2018b).

A study by Pandey et al. (2013) from Asian region representing Nepal, Cambodia, Lao PDR, and Indonesia has also come up with more or less similar causes of deforestation and forest degradation in the region, which includes conversion of forest land into agriculture land, illegal harvesting, infrastructure development, forest fires, encroachment, and grazing (Pandey et al. 2013). This study identified that conversion of forest land into agriculture land, illegal harvesting, infrastructure development, forest fires, encroachment, grazing, etc. are major causes in the region. These drivers are associated with various underlying factors mainly socioeconomic, and policy governance and the magnitudes of drivers are different in each country. These should be addressed with government intervention to change dependency on the forest resources, income sources of the people, and institutional setup of the forestry sector.

Consistent with the findings of these studies, the ERPD has also identified the following six major drivers of deforestation and forest degradation in the ER-Program area (REDD IC 2018a). Its findings were derived from various district-, regional- and national-level multistakeholder consultations. These drivers are

(a) Unsustainable and illegal harvesting of timber and fuelwood.
(b) Overgrazing.
(c) Forest fires.
(d) Encroachment/conversion of forest to other land uses.
(e) Resettlement.
(f) Infrastructure development.

It also recognized five major barriers to addressing the key drivers of deforestation and forest degradation effectively: limited financial resources and technologies to successfully implement programs; limited information and awareness on best management practices; governance and challenges associated with the transition to federalism; insufficient alternative livelihood and poverty alleviation opportunities; and conflicting views on sustainable management of forests.

Consequently, these drivers and underlying causes contribute to deforestation and forest degradation on the ground and the resulting carbon emissions into the atmosphere. Deforestation accounts for approximately two-thirds of land-based emissions in the Terai region, whereas forest degradation accounts for approximately one-third (REDD IC 2018a). These are mainly driven by an overall supply-demand gap for forest products, in particular for fuelwood and fodder, and illegal and unsustainable logging in government-managed forests. This is followed by unmanaged grazing, particularly outside community forests, which exacerbates these drivers and likely plays a role in inhibiting forest regeneration and enhancement in many areas (REDD IC 2018a).

20.4 ER-Program Interventions

A set of seven ER-Program interventions has been developed to address the drivers and underlying causes of deforestation and forest degradation. These interventions are implemented during the REDD+ implementation or demonstration phase of the ER-Program. Brief overviews of these interventions based on the approved Emission Reductions Program Document (REDD IC 2018a) are presented below.

20.4.1 Improve the Management Practices on the Existing Community and Collaborative Forests Building on Traditional and Customary Practices

Community forest (CF) and collaborative forest management (CFM) are two major forms of community-based forest management (CBFM) in Nepal, including the ER-Program area. Approved management plans for each CF and CFM area guide forest management activities on the ground. The ER Program is largely built on successful CBFM practices and aims to address key gaps to improve the sustainable management of forests. Under this first intervention area, forest management plans for existing community forest and collaborative forest management areas in the ER-Program area, covering approximately 280,000 ha and 60,000 ha, respectively, will be reviewed and updated to include sustainable forest management (SFM) practices (REDD IC 2018a). Consequently, this should improve carbon stock, sustain ecosystem services, and increase the supply of forest products not only to community and collaborative forest user groups but also outside the users' group. For this, forest management considerations will cover implementation of improved silvicultural systems for yield regulation, selective thinning, and natural regeneration promotion. Studies show forest carbon stock in CBFM areas to be significantly low (between 80 and 110 tC/ha) compared to average carbon stock in protected areas in the Terai region (291.55 tC/ha) (REDD IC 2018a). Therefore, CF and CFM forest user groups will be supported with the necessary technical skills and equipment to implement silvicultural operations, such as harvesting, thinning, pruning, and post-harvest operations, as prescribed by forest management plans, and to improve the condition of forests and forest products, including forest carbon stock. Primary interventions for improved forest management in both CF and CFM areas include identifying CF and CFM areas, holding discussions with forest users and stakeholders, determining silvicultural/management systems, conducting detailed forest surveys and forest inventories, preparing and approving detailed management plans, and monitoring management plan implementation on the ground (REDD IC 2018a).

20.4.2 Localize Forest Governance through the Transfer of National Forests to Community and Collaborative Forest User Groups

National forest in the ER-Program area is primarily government-managed forests and forests managed by CBFM groups. This program intervention endeavors to promote more localized CBFM modalities by gradually transferring national forest in the form of community and collaborative forests. Forests will then be managed by local forest user groups, which will ultimately support forest management and improve forest governance. Up until ER-Program formulation in 2018, some 380,000 ha of national forest had already been handed over to communities in the ER-Program area. The ER-Program plans to hand over another 200,000 ha of government-managed forests to community or collaborative forest management user groups; equivalent to 40% of remaining government forests in the Terai region (REDD IC 2018a).

Localizing forest management in the form of collaborative and community forest management brings multiple benefits for both forests and local communities. First, it decentralizes and delegates forest and forest product use rights to local communities. This practice not only improves rights for forest user groups in forest resource use and management, but also improves the overall productivity of the forests. Second, improved forest management and increased productivity in localized forest management also counter drivers of deforestation and degradation. For instance, increased forest monitoring and patrolling by forest users within their forests under localized forest management reduces different drivers of deforestation and forest degradation, such as illegal and unsustainable harvesting, forest fires, encroachment, and overgrazing (REDD IC 2018a).

As is the case for improved forest management, intervention areas under this program also include: identifying and mapping government-managed forests available for transfer as CF and CFM areas; identifying users (proximate to the forests and traditional users); registering forest user groups; conducting forest inventories and prescribing appropriate silvicultural system-based prescriptions in forest management plans; making approvals, and implementing forest management plans on the ground. These will be followed by monitoring and supervision of program implementation on the ground by the appropriate authorities. Taking the gender and inclusion considerations under the program, this intervention area has been designed to place adequate emphasis on women, indigenous and traditional users, including both poor and marginalized forest users.

20.4.3 Expand Private Sector Forestry through Improved Access to Extension Services and Finance

Private forestry and private sector engagement in the overall forestry sector in the ER-Program area could bring a suite of advantages, including environmental, social, and economic benefits. In the ER-Program area alone, around one million hectares of private land is under agriculture (REDD IC 2018a), which could be an avenue for promoting some form of private forestry or agroforestry practice in the region. However, there are currently only 639 registered private forests (PFs) in the program area, covering 550 ha of forests (REDD IC 2018a). This figure does not account for a larger portion of unregistered private forests. Still, the scale of private forests and private sector engagement in the overall forestry sector was inadequate in the program area.

Therefore, as a third program intervention, the ER Program set the target of incentivizing private forestry along with agroforestry on 30,000 ha of land over 10 years. Though agroforestry and kitchen garden areas might not be registered as private forests, they almost serve the very purpose of private forestry. This intervention is also in line with Nepal's targets under the Forestry Sector Strategy for 2016–25.

Under this intervention, long-term, low-cost capital along with appropriate seedlings and training will be provided to small-scale landholders to incentivize plantation and maintenance of forests on their private lands. For example, local resource persons and local-level forestry staff will be trained in various aspects of private forestry, including nursery management, silviculture practices, disease and pest management, soil fertility and nutrient management, and harvesting and post-harvest handling through site visits and demonstration sites. As a result, private forestry is expected to improve multiple ecosystem services through reduced erosion and landslides, protection of downstream water supplies, and reduced risk of flooding and sedimentation and by increasing soil carbon and above-ground biomass in intervention areas (REDD IC 2018a).

Beyond private forestry, these program interventions also seek to enhance private sector engagement in forest management. For this, the Forest Act has stipulated a provision for managing forests above 500 ha in area under government-private sector partnerships. Further, the role of the private sector in forestry can also be explored in many aspects of community forest management, such as forest management plan preparation and implementation of silvicultural treatments and forest management activities.

Unlike the agriculture sector, privately run forestry operations require long-term rotation cycles, and financial returns limit the expansion of private forestry and private sector engagement in the forestry sector. Engagement of the private sector in forest management and private forestry under this intervention should focus on both short-and long-term products, as well as returns to investors while supporting supplies of forest products, environmental amelioration, employment generation, and emissions reductions.

20.4.4 Expand Access to Alternative Energy with Biogas and Improved Cookstoves

The program intervention on access to alternative energy with biogas and improved cookstoves was designed to address drivers of deforestation and forest degradation in the ER-Program area indirectly. The program has set a target of installing additional 12,000 biogas plants per year in the ER-Program area (REDD IC 2018a). Given the fact that the use of fuelwood for cooking was found to be one of the drivers of deforestation and forest degradation, this intervention was designed to reduce pressure on forests for fuelwood through the use of alternative energy. This will also reduce emissions from fuelwood consumption. To complement the biogas plants and reach more households, the Government of Nepal will build on its Clean Cook Stove Initiative and install an average of 2000 clean cookstoves per district per year in each of the ER-Program districts, or a program-wide total of 24,000 clean cookstoves a year (REDD IC 2018a). Both initiatives will be implemented through the existing Alternative Energy Promotion Centre (AEPC) program, which will receive additional financing from the ER Program to support further rollout in the TAL.

20.4.5 Scale Up pro-Poor Leasehold Forestry

The ER Program has set another intervention to scale up pro-poor leasehold forestry (LF) in the TAL area. It aims to expand the leasehold forestry program, which has been successful in providing employment opportunities to poor communities in other parts of Nepal, on approximately 12,000 ha in the program area (REDD IC

2018a). Altogether there are more than 7000 leasehold forest user groups in Nepal, managing over 40,000 ha of LFs and involving over 62,000 families (REDD IC 2018a). The program has helped support these families through the production of forage crops, fodder, agroforestry products, medicinal and aromatic plants, and other non-timber forest products. The pro-poor LF will also help to reduce forest degradation from unmanaged forest exploitation. Despite being successful in other parts of Nepal, the pro-poor leasehold forestry program has only been implemented in the Chitwan and Nawalpur districts of the program area. Therefore, this intervention was proposed to scale up the program to all 13 districts of the TAL region.

20.4.6 Improve Integrated Land-Use Planning to Reduce Forest Conversion Associated with Advancing Infrastructure Development

This intervention includes several components to improve and integrate land-use planning to reduce forest conversion. This requires developing detailed maps, zoning all CBFM areas and potential resettlement areas delimiting potential sites for afforestation and reforestation, including for new plantations for private commercial forestry operations. This intervention was also designed to support municipalities in infrastructure zoning by developing land-use plans for the concerned rural and urban municipalities integrating development and traditional land-use practices. Therefore, the overall goal is to reduce deforestation through integrated land-use planning and implementation in infrastructure development in the ER program districts. It has set the target of reducing around 9000 ha of forest conversion associated with infrastructure development through improved integrated land-use planning (REDD IC 2018a).

Under this component, the National REDD+ Steering Committee – the apex body chaired by the Minister for Forests and Environment and including the key ministries responsible for land-use planning—will coordinate land use and land-use change plans and proper regulation and monitoring of environmental impact assessments in tandem with relevant stakeholders.

20.4.7 Strengthen Management of Protected Areas

Protected areas are well maintained in Nepal through various conservation measures and are not subject to historical deforestation and forest degradation. These areas are only included in the ER Program for the significant non-carbon benefits they provide and to safeguard against any social and environmental impacts (e.g., human–wildlife conflicts) that could arise due to implementation of the ER Program. There are six protected areas in ERPD districts, including five national parks and one conservation area, which serve as environmental safeguards in the region.

Based on the approved ERPD, the seven program intervention areas together with their set targets are summarized in Table 20.1 below.

Table 20.1 Summary of ER-Program interventions and set targets (Source: REDD IC 2018a)

SN	Intervention	Target
1	Improve management practices on the existing community and collaborative forests building on traditional and customary practices	336,069 ha
2	Localize forest governance through the transfer of national forests to community and collaborative forest user groups	200,937 ha
3	Expand private sector forestry operations through improved access to extension services and finance	30,141 ha
4	Expand access to alternative energy with biogas	60,000 units
5	Scale up pro-poor leasehold forestry	12,057 ha
6	Improve integrated land-use planning to reduce forest conversion associated with infrastructure development	11,736 ha
7	Improve management of existing protected areas (PAs)[a]	6 PAs

[a]This activity will not directly contribute towards ER, but enhance NCBs and environmental safeguards. Even though PA contribute to conserve and enhance forest carbon stocks, the emissions reduction/removals from these activities will not be claimed for the results-based payments

Set targets are broken down further into district-wide targets under each program intervention. With reference to the approved ERPD 2018, Table 20.2 shows targets under each ER-Program intervention area by district.

20.5 ER-Program Interventions and Drivers of Deforestation and Forest Degradation

As discussed in the previous sections, the Emission Reductions Program Document has seven areas of intervention and six major drivers of deforestation and forest degradation in the program area (Table 20.3). The seven ER-Program interventions were designed to address the drivers of deforestation and forest degradation in the program area. Table 20.3 below summarizes how these program interventions help address the drivers of deforestation and forest degradation in the ER-Program area in southern Nepal.

Though there are seven program intervention areas, only interventions one to six are designed to contribute to emissions reductions. The final intervention on improved management of existing protected areas does not directly contribute towards emissions reductions but amplifies other non-carbon benefits and environmental safeguards in the region.

Of the remaining six program interventions, the first and second, which focus on improved management of existing CBFM areas and transfer of government-managed forest to collaborative and community forest users, respectively, constitute a more than two-third weightage of ER-Program interventions. This is not only from the perspective of program interventions and activities designed to address drivers of deforestation and forest degradation but is also based on set emission reductions targets. Table 20.3 above also shows these two program interventions are expected to address all five of the six drivers, with the only exception being infrastructure

Table 20.2 ER-Program interventions and targets set for each district

Program district	1. Improve management of CBFM (ha)	2. Transfer government forest to CBFM (ha)	3. Scale up private forestry (ha)	4. Expand alternative energy (HH)	5. Pro-poor Leasehold Forestry (ha)	6. Integrated land use planning (ha)
Rautahat	16,800	3630	544	5952	218	259
Bara	15,716	12,106	1816	7406	726	460
Parsa	11,647	198	30	6387	12	758
Chitwan	18,055	12,165	1825	6593	730	1417
Nawalparasi	17,485	34,443	5166	9202	2067	1036
Kapilbastu	30,483	11,417	1713	5827	685	251
Rupandehi	12,772	4933	740	5065	296	590
Dang	103,151	35,812	5372	8937	2149	1927
Banke	27,760	13,440	2016	6850	806	1164
Bardia	18,812	–	–	7324	0	1116
Kailali	47,036	60,481	9072	12,302	3629	1982
Kanchanpur	16,352	12,311	1847	6784	739	776

After the approval of ERPD, Nawalparasi district is divided into two districts Nawalpur and Parasi making 13 ER program districts

Table 20.3 Emission reductions interventions for addressing drivers of deforestation and forest degradation

ER Intervention	Drivers	Justification
1. Improve the management practices on existing community forests building on traditional and customary practices	Unsustainable harvest (timber/ fuelwood)	• Improved supply of timber and fuelwood from improved forest management reduces unsustainable and illegal harvesting
	Overgrazing	• Integrated grazing including stall feeding in CBFM areas
	Forest fires	• Fire management training and community-based fire management occur in CBFM
		• Improved silvicultural practices will reduce uncontrolled fire risks
	Encroachment	• Establishing community forests provides clear management rights, boundary delineation, and increased patrolling, all of which reduce encroachment and conversion
	Resettlement	• Improved enforcement and management in CBFM areas will decrease unplanned resettlement that is more common in government-managed forests
2. Localize forest governance through transfer of national forests to community and collaborative forest user groups:	Unsustainable harvest (timber/ fuelwood)	• Localized governance and increased monitoring/patrolling of forests transferred to communities reduces illegal and unsustainable harvest
	Overgrazing	• Increased enforcement and management in CBFM areas will regulate and control grazing
	Forest fires	• Fire monitoring and early warning system in localized CBFM will reduce the spread of uncontrolled fires
		• Construction of fire lines delineates management blocks for forest management in community and collaborative forests
	Encroachment	• Improved management under localized CBFM reduces unsustainable logging practices, and conversion of forest to other land uses

(continued)

Table 20.3 (continued)

ER Intervention	Drivers	Justification
	Resettlement	• Improved enforcement and management in CBFM areas will decrease unplanned resettlement that is more common in government-managed forests
3. Expand private sector forestry	Unsustainable harvest (timber/ fuelwood)	• Improved supply of timber and fuelwood from private forests reduces unsustainable and illegal harvesting
4. Expand access to alternative energy	Unsustainable harvest (timber/ fuelwood)	• Alternative energy programs decrease demand driving unsustainable fuelwood harvesting
	Overgrazing	• Incentive is created to maintain cattle for biogas plants
5. Scale up pro-poor leasehold forestry	Overgrazing	• Improved livestock management occurs under leasehold forestry programs
6. Improve integrated land-use planning to reduce forest conversion associated with advancing infrastructure development	Unsustainable harvest (timber/ fuelwood)	• Improved land-use planning will reduce the deforestation impacts of infrastructure development
	Encroachment	• CBFM provides an avenue for communities to align with federal encroachment policies
	Resettlement	• Land use planning intervention will improve federal, state, and local planning for appropriate resettlement management
	Infrastructure development	• Improved land-use planning will reduce the deforestation impacts of infrastructure development
		• Improved coordination among agencies and consultation with stakeholders will reduce unnecessary conversion and support wildlife corridors
		• Land-use planning intervention includes activities for better implementation and enforcement of EIA requirements

development. For example, improved management in existing CBFM areas helps reduce unsustainable harvesting through an improved supply of timber and fuelwood from improved forest management. It also addresses the overgrazing problem through integrated grazing, including adopting stall-feeding practices in collaborative and community forests. In addition, having clear forest management plans and management rights also helps forest users tackle other drivers, such as encroachment, conversion of forest to other land uses, and unplanned settlement in forest areas through regular forest management and monitoring. Similarly, the second program intervention on localizing forest governance through the transfer of government-managed national forest to CF and CFM user groups also helps address key drivers, such as unsustainable and illegal timber and fuelwood harvesting, through increased monitoring, patrolling, and localized forest management practices. Forest user groups also help regulate and control grazing and forest fire incidents through firebreaks, early warning systems, and fire monitoring activities. Furthermore, localized CBFM reduces unsustainable logging practices, unplanned resettlement, and conversion of forest for other land uses.

Infrastructure development was identified as another key driver of deforestation and forest degradation in the ER-Program area. Accordingly, the sixth intervention, on improving integrated land-use planning to reduce forest conversion associated with advancing infrastructure development was designed to address this driver. This intervention is expected to improve land-use planning to reduce deforestation impacts of infrastructure development, including implementation and enforcement of environmental impact assessment requirements, and improved stakeholder coordination to reduce unnecessary conversion of forest. Integrated land-use planning also helps tackle other drivers, such as unsustainable timber harvesting, encroachment, conversion for other land uses, and resettlement on forest land.

The remaining three program interventions are also designed with specific activity/intervention areas, and will help address specific drivers of deforestation and forest degradation. For instance, the intervention on expanding private sector forestry helps address the issue of unsustainable fuelwood and timber harvesting through the supplying of such products from private forests. Similarly, scaling up pro-poor leasehold forestry addresses overgrazing practices through improved livestock management practices under the leasehold forestry program. Likewise, the fourth program intervention on expanding access to alternative energy is primarily expected to address two drivers in overgrazing and illegal timber and fuelwood harvesting. As alternative energy in the form of biogas plants and improved cooking stoves decreases demand for fuelwood for cooking, this will ultimately reduce pressure on forests. Similarly, biogas plants create incentives for farmers to stall-feed cattle for biogas, thereby reducing pressure on forests from overgrazing.

20.6 ER-Program Implementation

The Ministry of Forests and Environment (MoFE), REDD Implementation Centre is responsible for the overall management and coordination of ER-Program implementation and distribution of ER payments to beneficiaries. However, ER-Program activities are executed by various government institutions, including the Department of Forests and Soil Conservation, Department of National Parks and Wildlife Conservation, provincial offices of the Ministries of Industry, Tourism, Forests and Environment, the Forest Directorate, Division Forests Offices and CBFM groups. Monitoring, reporting, and verification (MRV) and the emission reductions database are managed by the Forest Research and Training Centre (FRTC) under the MoFE. Costs for the initial phase of the ER-Program until 2025 are estimated at USD 101 million. This includes costs relating to administrative oversight, implementation of the seven ER-Program interventions, emissions reductions measurement and monitoring as well as environmental and social risk mitigation measures (REDD IC 2018a).

The ER Program in the Terai Arc Landscape of Nepal is among the first of its kind worldwide. Nepal will also be the first and only country in South Asia to receive results-based payments for emissions reductions from the REDD+ program under the FCPF Carbon Fund along with countries in other regions, such as the Democratic Republic of Congo, Ghana, Mozambique, Costa Rica, Chile, Indonesia, Vietnam, and Laos.

The ER Program is designed to address identified drivers of deforestation and forest degradation over a 10-year period from 2018 to 2028 in the Terai Arc Landscape region of Nepal. With its seven intervention areas, the ER program is expected to generate emissions reductions of 34.2 $MtCO_2e$ during the program period of 10 years. The ER Program has also allocated 23% of generated emissions reductions to a buffer based on estimated uncertainty of ERs (12% conservativeness factor) and risk of reversal of 11% (REDD IC 2018a).

In February 2021, the Government of Nepal signed a landmark Emission Reductions Payment Agreement (ERPA) with the World Bank's Forest Carbon Partnership Facility for the first 6 years of ER program. With this ERPA in place, Nepal is expected to reduce emissions by 9 $MtCO_2e$ in the Terai Arc Landscape for the first six years of ER program unlocking up to USD 45 million in payments for reducing carbon emissions from deforestation and forest degradation. Based on its emissions reductions performance, Nepal can claim results-based payments in 2022 and 2025. The agreement also has a provision for retroactive accounting of emissions reductions from interventions conducted between ERPD approval in 2018 and the ERPA being signed in February 2021.

Other important considerations in the ER Program are social and environmental safeguards during program implementation in order to maximize benefits for people in the program area as well as for forests and biodiversity in the Terai region. For this, the Government has prepared and approved an environmental and social management framework to address the issue of safeguards. Similarly, it has made a benefit-sharing plan outlining benefit-sharing arrangements for results-based payments (REDD IC 2019). This determines how benefits from the ER Program will be distributed to the various stakeholders engaged in the program. Project beneficiaries are those who contribute directly to the implementation of emissions reduction activities in the ER-Program area, thereby contributing to reduced deforestation and increased forest carbon stock. These beneficiaries include: government; community-managed forest groups (community, collaborative, leasehold, and religious forest groups); private forest owners; and households not belonging directly to community-managed forest groups.

20.7 Conclusions

The Emission Reductions Program in the Terai Arc Landscape of Southern Nepal provides a unique opportunity to address drivers of deforestation and forest degradation and reduce emissions from the program area. In addition, it unlocks the opportunity for results-based payments for emissions reductions, and carbon stock enhancement through sustainable management of forest resources. The program's seven intervention areas—focusing primarily on improved forest management in community-based forest management regimes, promotion of private and leasehold forestry, alternative energy and integrated land-use practices—are being implemented in the field to help achieve the program's overarching goal of reducing emissions from deforestation and forest degradation.

Potential benefits from the ER Program depend solely on the performance of program interventions; the better the performance, the greater the benefits. The program is indeed the first results-based payment, forest-based emissions reductions program of its kind in Nepal. It has set district-wide targets for each of the program's intervention areas and their potential contributions to emissions reductions. For example, with the potential 34.2 $MtCO_2e$ during the ER-program period of 10 years, Nepal can generate emission reductions of 9 $MtCO_2e$ and receive the result-based payment of up to USD 45 million for the first six years of ER program. To fully realize the potential benefits of the ER Program, it is high time to implement each program intervention component effectively on the ground. Doing so will not only help address the drivers of deforestation and forest degradation but will also help achieve the emissions reductions targets set for Nepal's eligibility for results-based payments as envisioned in the Emission Reductions Program Document. Further, lessons learned from ER-Program interventions in the Terai Arc Landscape region under the REDD+ program will be useful when implementing similar interventions in other landscapes in Nepal in the future.

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Public Interests and Private Incentives in Designing an Ecological Payment Systems

21

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Abstract

An important class of market-based mechanisms is known as payments for ecosystem services (PES). The overall aim of this study is to assess the main opportunities for a PES in selected areas of Azerbaijan and investigate on the assessment of its impact, development, and potential through the implementation of a field study, based on surveys and interviews. The surveys' results suggest that positive attitudes towards market-friendly schemes are widespread across potential participants. Econometric analysis further shows that willingness to accept levels depend on key variables such as incomes, information, and gender, but basic levels tend to be high regardless of these variables. This in turn indicates that the crucial element of willingness to participate are already present in the population interested and that future application of PES schemes are likely to meet with general consensus. Even though they present implementation challenges because of their innovative design and lack of previous experience of both private and public parties, PES appear thus to have good chances of succeeding because of the attitude of the potential participants. By creating market-based mechanisms for environmental protection, which can potentially spread to many sectors and areas of the country, they thus appear to be a good choice to steer public policies and private behavior toward more sustainable management systems of natural resources.

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Payment for Ecosystem services · Ecosystem valuation · Soil erosion · Freshwater ecosystems · Willingness to pay · Willingness to accept

21.1 Introduction

In view of growing concerns on ecosystem degradation, it is very important to develop market-friendly policies to manage ecosystems in a more sustainable way. In order to promote conservation and protection of natural resources and improve ecosystem services, in particular, various types of market driven mechanisms can be designed (Bingham et al. 1995; Scandizzo and Knudsen 1996). An important class of such mechanisms is known as payments for ecosystem services (PES) (Garcia and Wolff 2014). Through PES, landowners are supported financially to change their land use styles and provide ecosystem services to buyers. These buyers can be direct users or non-users interested in improving ecosystem services. Almost in all PES schemes, stakeholders are paid to manage their resources more effectively, protect land, biodiversity, carbon sequestration ability through, for example, replanting trees, reducing grazing, and applying more nature-friendly agricultural methods (Redford and Adams 2009).

Unlike conventional instruments of agricultural policies, such as tax relief, subsidies, and extension programs, PES aim at empowering stakeholders such as farmers, villagers, and other operators from the government and the private sector (Milder et al. 2010; Costanza et al. 1997). Rather than focusing on productivity increases for selected agricultural goods, PES systems concentrate their attention on the potential of stakeholders, their individual capabilities, and the improvements that can be obtained by upgrading their skills, enhancing their management capabilities and integrating production and conservation activities. By expanding stakeholders' opportunities, PES thus create "real options." This is a relatively new concept in economics which has proven very useful to identify and quantify the opportunities created by successful development programs. In analogy with a financial option, a real option is defined as the faculty, but not the obligation, of undertaking a given action at a pre-determined cost. This definition is simple and operational and does not seem to depend on uncertainty, irreversibility, or the other special characteristics that are generally invoked (see, for example, Pindyck 2000; Damodaran 2002). By identifying a separate class of claims, that, at the same time, do not create counterpart obligations, its implications also shed new light on key concepts of law and economics, such as empowerment, vesting of rights and the nature and interests of stakeholders (Graham 2005). Unlike the financial option, a real option does not necessarily depend on a formal contractual relation, but on a commitment of resources without the possibility of full recovery. Such a commitment, which in the case of PES is constituted by the fixed payment to the farmers, creates a sunk fund, with no apparent opportunity cost (bygones are bygones). This virtual fund has a counterpart in the voluntary adoption on the part of the farmers of a series of practices and training activities aimed to integrate production and conservation. The virtual fund created by PES has thus a potential value, since it constitutes a capability to explore future opportunities in management and investment. It is this potential that generates new options as added faculties of the participants to the program (Garcia and Wolff 2014).

In Azerbaijan, agriculture accounts for about 5% of GDP and 37% of employment. The present regime of government intervention is based on tax exemption, credit and input subsidies, and direct subsidies to farmers for production of agricultural goods. From the point of view of a sustainable pattern of production, the combination of population pressure, general subsidization, and unregulated land and input use appears to have resulted in severe damage to the environment (Abbasov and Smakhtin 2012; Babaev et al. 2015; Shelton 2003). These include a high and progressive level of soil erosion and extensive deforestation. Overgrazing and illegal logging are the main issues that concern current land use activities. Recent activities make the area very vulnerable in terms of land degradation and erosion that in turn reduce quality of ecosystems and ecosystem services provided by grassland and forests (Abbasov 2014; Abbasov 2018).

The overall aim of this study is to collect valid and reliable information and identify opportunities for future PES markets in Azerbaijan and the target area, assess main opportunities for future PES markets, and provide a roadmap to full PES implementation. The study thus investigates the impact, development, and potential of a system of Payments for Environmental Services (PES) in Azerbaijan through the implementation of a field study based on surveys and interviews. This task is performed following the scheme of sustainable development and the specific function that this form of alternative policy intervention accomplishes for community's well-being, environmental preservation, and economic development. Within this broad theme, the study had a number of specific objectives:

- To identify the existing ecosystem services of forest and high alpine grasslands in Ismailli and Shamakhi districts of Azerbaijan and classify them.
- To identify target groups, sellers, and buyers for future PES markets.
- To collect the needed data for PES.
- Identify institutional and administrative functions/frameworks (who can be the body to manage the ecosystem services).
- Develop pro-poor benefit-sharing mechanisms (mechanisms piloted to reduce over-grazing and restore critical ecosystem services generated by healthy summer pastures (forests) in the Greater Caucasus Mountains.
- Interlink PES with Pasture Users' Associations and Forest Users' Associations established in the region and identify income sources for PUA and FUA.
- Prepare and submit the final draft report with the road map for the year 2017 to international expert and to UNDP.
- To design WTP (Willingness To Pay) questionnaire of non-use values of ecosystems for potential buyers and pretest it.

21.2 PES as a New Market-Environment-Friendly Instrument

The PES is a form of a contract that parallels, for certain aspects reproduces, and for other mirrors, the concession contract. While a concession contract typically aims to promote the development of a natural resource or other public resource efficiently, taking into account the public good, a PES has the objective of avoiding or restraining development of the resource in order to pursue one or more conservation goals. While the concession generates rewards to the holder through exclusive rights over the use of the resource, the PES seeks to limit the right of the owner or user of the resource, paying in exchange a compensation. In the case of PES, therefore, it is the government that is, in a certain sense, the concessionaire, while the private party is the granter of the concession in exchange for a fee. As shown by Scandizzo (2009) and Scandizzo and Ventura (2015) in the case of the concession contract, the form of "reverse concession" constituted by PES has a number of interesting properties and, while potentially advantageous for both the community and the private owners, should be handled with care.

The first property of PES is that it seeks to align private and public incentives, recognizing the difference and properly charging the costs of the alignment to the public. In order to understand what is the possible role of PES, however, one does not have to limit oneself to imagine a pure transfer of payments to a set of private holders of rights over natural resources. Equally important, in fact, is the issue that privatized natural resource uses may have on the role of government. In this respect, a special position is assumed by the so-called "fundamental theorem of privatization," stated in 1987 by two American economists (Sappington and Stiglitz 1987). This theorem, which in a short period, has become the basis of innovative thinking on the relations between property and enterprise, turns upside down the traditional approach that sees normality as the condition in which property is private and the regime change is constituted by the attenuation of private control in favor of the public authority. By considering the opposite hypothesis of transfer of rights from the public to the private sector, this approach proposes to identify the conditions under which a complete delegation of production decisions to a private concern is socially desirable. The basic idea of the theorem, which identifies some stringent conditions under which the above social desirability exists, is basically a PES system, that is, an auction mechanism whereby a certain number of firms compete to acquire the right to produce a good or a service, for which a relevant public interest exists. The auction mechanism ensures separation between the public concern (the "government"), which opens the auction, and the winner (the private concern). It is designed, however, in a way that makes compulsory for the winner to pursue one or more public objectives (for example, the production of a given amount of environmental services, the maintenance of the resource according to given standards). As a consequence, the winner, even though she is completely distinct from it, shares with the government the objective function, having won the auction, and having to deliver the objectives, conditioned to sustaining the effective costs, which are thereby minimized.

According to the logic of the theorem, therefore, a PES system can be rationalized as a form of public intervention that preserves the separation of property from enterprise, which is characteristic of the capitalistic organization of production. PES make, in fact, possible to privatize the pursuit of public interests, by preserving private property rights and utilizing at the same time private concerns as the most efficient instrument of environmental conservation in a market economy. The conditions under which this perfect efficiency is achieved, however, cannot possibly hold in reality: they include, in fact, absence of risk aversion on the part of the firms, perfect competition, no transaction costs, no possibility of collusion, and perfect information.

Accepting such a process as the best solution to the problem of achieving social efficiency under private ownership, two different economists, Laffont and Tirole (1986, 1988), have put forward a more daring theory. According to this theory, the separation between property and enterprise in modern capitalism requires a particular regulatory environment because it is the result of an incomplete constitution. The constituents (the founding fathers), since they operate under a veil of ignorance, are unable to design a complete set of rules (a constitution) that predicts and describes costlessly all future contingencies. If they were able to do so, the economy would be composed of only private subjects, while constitutional rules would be reduced to a set of detailed instructions that the private subjects would have to follow. The only public subjects would be, in this case, the courts of justice, which would have the task to make sure that the private subjects followed the instructions as prescribed by the constitution.

In the conditions of uncertainty that characterizes the actions of the founding fathers, the rule that can be emanated cannot be detailed instructions, but only meta-rules, constraints, and prescriptions of general type. Public agents are not any longer limited to the courts of justice: their role is more important precisely because their mandate is vague and does not include explicitly all the possible contingencies. One part of public agents (the bureaucrats) has the task to manage the lack of specific prescriptions.

An organizational form, which in a stylized form can be described as consisting of four components, may represent the problem of reconciling public concerns and efficiency, under these conditions: (a) the firm, (b) the agency, (c) the founding fathers and, (d) the consumers. The firm is a private concern that operates according to the principle of maximum profit or, where applicable, the minimum cost. It is characterized by variable costs that are common knowledge, and by fixed costs, technology, and effort levels known only to management. The agency is endowed with regulatory and control power based on the constitution and the related system of laws. It may involve property rights relative to the operations of the firm. For example, it may be assigned control rights for the firm, or discretionary power to concede or revoke the authorization to operate, or to nominate or revoke the administrators. The main role of the agency is to make sure that correct information on the firm's structure (technology, profits, benefits of managers and dependents) is passed on to the community. In doing so, however, the agency is tempted to collude with the firm, by sharing the advantages that can be gained at the expenses of the consumers. The agency thus receives a pay-off only if its behavior is beyond reproach both in terms of effort and in the lack of collusion with the firm. The founding fathers, via legislation or executive action, give the agency its mission and empower other organs of the judicial system to monitor and control its performance.

As an exemplary application, Laffont and Tirole (1986, 1988) analyze the prohibition, common to many juridical systems, to make transfers to public operations or to private firms operating under regulation, to cover their losses. When the activity faced by the firm presents increasing returns to scale, in fact, social efficiency implied by the so-called marginal cost rule (which wants the price of the service provided to the public just enough to cover the service cost) requires the transfer to be made. Application of the alternative average cost rule, on the other hand, is compatible with the absence of losses on the part of the firm, but not with social efficiency. In the case of forests, this dilemma is exemplified by parastatal operations of various forms (Public Forest Administrations or PFAs), whose existence is justified by the fact that forests provide both private goods and a variety of externalities. Most of PFAs have indeed accumulated large losses, which, at least in part, can be attributed to their providing services over and above what mere private firms would provide.

According to the Laffont and Tirole (1986, 1988) argument, however, substituting a combination of private concessions and PES to PFA's operations would have the likely benefit to increase efficiency and avoid the collusion between the regulators and the firm (the parastatal operation or the concession holder). This would be achieved because the fact that PES de-couple the conservation payments from the management costs would mean that the government cannot intervene to fill the difference between revenues and costs of the regulated firm and this creates a conflict of interest between the consumers and other social groups and the possibly colluding regulators and regulated. Thus, consumers, grass-roots social groups, environmental and business groups may be motivated, if information costs are relatively low, while collusion costs are high, to control both the firm and the regulators to avoid collusion. This result may be mixed in some respect, but in its totality may have a greater efficiency than the usual bail-out in the name of public interest.

21.3 A PES Typology

Several types of PES schemes have been experimented on with various degrees of success all over the world. These schemes mainly include direct payments to landowners or their indirect support. Direct payments may include contracts between buyers (generally public bodies) and sellers (generally private parties), where buyers directly support service providers. Government subsidies, tax reductions, different types of programs through which farmers are financially supported to reduce soil erosion may be counted as direct payments (Grima et al. 2016). For example, a government program that is concerned with land degradation may provide financial support of landowners and help them to implement proper measures against land degradation. It may also be an experiment launched by government to find what types of land use patterns will provide more gains. Reverse auctions over the land-use permits can also be counted as direct payments. In land-use reverse auctions, government (or another buyer) purchases land-use rights from the owners in an auction, where many landowners offer their rights at a bid price. Land use rights may be purchased through direct negotiations with landowners. Parties may agree on foregoing rights for fixed periods of time (usually for 10–15 years) to the buyer and use their lands only for specific purposes, through which sustained ecosystem management will be maintained.

In some, program's landowners are supported indirectly. Under indirect payments, for example, certain types of activities can be freed from taxes. Farmers may choose more sustainable activities through which land and ecosystems will be protected. For example, switching to beekeeping instead of cattle breeding in mountain regions can be supported by tax reductions.

PES types may be private, public, or cap & trade (Zhen and Zhang 2001). In private, PES parties directly talk to each other through agreements and contracts. The parties include landowners, government, charity foundations, or companies that are interested to improve quality of ecosystem services. For example, in private PES activities that are implemented in the USA, government and charity foundations directly support landowners**.** İn most cases, buyers buy use rights of lands and property rights remain in landowners.

In some cases, public PES schemes are similar to private PES schemes. However, public PES schemes mainly come as subsidies or tax reductions. In these kind of schemes, buyers may motivate landowners through various kinds of incentives that include reduction of taxes, subsidies, and government purchases.

Cap and trade schemes can be considered as indirect PES. For example, landowners can be given quotas to water abstraction or pollution. Within the designed PES schemes, these quotas may be subject to trading. These kinds of PES schemes cannot be implemented in all countries. For example, water quotas may be subject to trade only in countries with high water shortages, where a solid background of environmental laws exists (Fig. 21.1).

While the PES schemes may have various origins and forms, they all are directed to reduce human pressures on ecosystems using the way that could be reasonable and practical. PES schemes sometimes may deny some short-term gains of stakeholders, bringing benefits for all sides in the long term. In other words, PES schemes make ecosystem protection economically profitable and ensure sustainable use of resources.

In most of developed countries, several forms are successfully applied. Most used PES formulas have following patterns:

- Government subsidies landowners to change land-use type.
- Landowners supported to reduce grazing through rotational grazing.
- Landowners supported to reduce pasture grazing through special quotas.
- Landowners supported to reduce water withdrawals though water saving technologies.

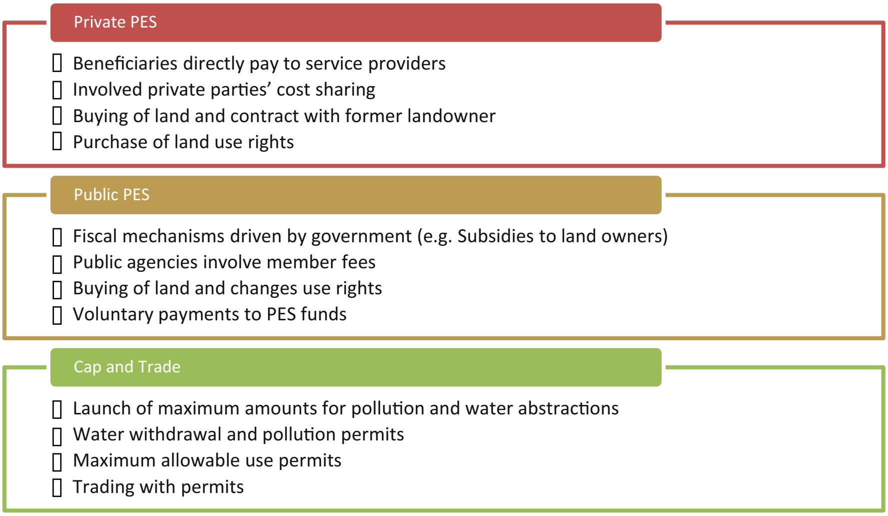

Fig. 21.1 Main PES types and their mechanisms

- Landowners supported to change land-use type.
- Purchase of land-use rights through reverse actions for 10–15 years.

21.4 Environmental Valuations

As a system of payments whose effectiveness depend on costs and benefits of the parties involved, PES design and implementation are crucially linked to the issue of properly valuing the environmental services to be provided. In this respect, contractual typologies become relevant. Some authors distinguish between contractual arrangements (CRES), compensations (CES), and rewards (RES) for ecological services (Scandizzo and Notaro 2008). They define these three categories as follows: "CRES are contractual arrangements and negotiated agreements among ecosystem stewards, environmental service beneficiaries, or intermediaries, for the purpose of enhancing, maintaining, reallocating, or offsetting damage to environmental services." A particular CRES contract or negotiated agreement will include a compensation or reward instrument or combination of instruments:"Compensation for Environmental Services" (CES) are payments or other forms of restitution made to environmental service beneficiaries or ecosystem stewards to offset foregone entitlements to environmental services or ecosystem stewardship benefits.

- CES1—Compensation to environmental service beneficiaries for socially disappointing damage to ecosystem services by ecosystem stewards. This includes self-organized deals between stewards and beneficiaries, restitution payments ordered by intermediary organizations, and compensation payments made by intermediary organizations.

- CES2—Self-organized contracts, negotiated agreements, or tradable allowance and permit systems that facilitate exchange of environmental service entitlements among environmental service beneficiaries. This includes cap-and-trade systems for emissions and conservation concessions.

"Rewards for Environmental Services" (RES) are inducements provided to ecosystem stewards to give them incentive to enhance or maintain environmental services.

- RES1—Rewards to ecosystem stewards for foregone stewardship rights or reduction of threats. This includes self-organized deals between ecosystem stewards and environmental service beneficiaries, public programs of reward made on behalf of beneficiaries, and eco-labeling and certification schemes for products generated through good stewardship practices.
- RES2—Rewards to ecosystem stewards for undertaking extra investments or management practices that restore or enhance the ecosystem. This includes self-organized deals and public programs of reward.

Dixon and Pagiola (2001) distinguish between biological **resources** and biological **diversity**, where the former refers to a gene, species, or ecosystem, while the latter refers to the variability of the resources. This first distinction is necessary to achieve a suitable green accountancy which can contribute to the normal accounting system of an economy and, on its basis, enhance a series of interventions and investments for the preservation of the biodiversity. The difficulty of the evaluation can result in an inadequate management of the ecosystem and, consequently, in a scarcity and tended extinction of ecosystem services, but it can be attenuated by distinguishing several evaluation components and evaluating each of them separately. This is typically done by considering biodiversity Total Economic Value (TEV), which can be decomposed into the use value, including direct, indirect, and option value and non-use value, including bequest and existence value. Table 21.1 shows a synthesis of several methodologies developed to "valuate," i.e., to assign specific values, to ecosystem services.

To analyze the "stated preferences" of tourists for the consumption of ecotourism services and for the conservation of cultural and natural heritage, this section will gather relevant information to implement policies to finance preservation and endogenous economic development. This section will be also important to determine part of the total economic value for ecosystem services, especially the contribution for non-use value. The rationale of this section is the need to ascertain the interviewees' opinions and sensitivity with respect to the main environmental problems, thus providing indications for policies and financing sources on cultural and economic issues in the contest of ecotourism management. Willingness to pay is also functional to measure the total economic value of ecosystem services.

Willingness to pay, as well as willingness to accept measures are elicited in the context of the Contingent Valuation Methodology (CVM), a procedure widely used

Table 21.1 Valuation methods (Source: Brander et al. 2012)

Valuation method	Short description	Welfare measure
Contingent valuation	Hypothetical questions to obtain WTP	Compensating or equivalent surplus
Travel cost	Estimate demand (WTP) using travel costs to visit site	Consumer surplus
Hedonic pricing	Estimate WTP using price differentials and characteristics	Consumer surplus
Production function	Estimate value as an input in production	Producer and consumer surplus
Net factor income	Assign value as a revenue of an associated product net of costs of other inputs	Producer surplus
Replacement cost	Cost of replacing the function with an alternative technology	Value larger than the current cost of supply
Opportunity cost	Value of next best alternative use of resources (e.g., agriculture use of water and land)	Consumer surplus, producer surplus of total revenue for the next best alternative
Market prices	Assigns value equal to the total market revenue of goods/services	Total revenue

in the context of valuation of goods with no market prices, such as many environmental goods. In this context, the value assigned refers to non-use value or nonmarket use value or both.

A typical CVM survey in environmental studies starts with the familiarization of the interviewee with a project proposal on the environmental good or resource. The project proposal aims to identify an improvement of the environment and a method to finance it. On this basis, the interviewee is requested to answer questions about the willingness to pay (WTP) for the improvement.

The WTP questions can be structured in several ways and may be organized in open-ended patterns, bidding games, payment cards, and dichotomous choices. The open-ended pattern consists in simple questions on the maximum willingness to pay for the interviewee for the project identified. This method is not very often used because of the difficulty for the interviewees to answer the question, resulting in many missing WTP values. In the bidding game approach, instead, interviewees are asked if they are willing to pay a certain amount and then, if the answer is yes (or not) to increase (decrease) the amount until the answer is negative (positive) with the last answer to be interpreted as WTP. The criticism to this approach is that there might be a starting point and a final WTP bias, and a non-reliable answer from interviewees who are impatient to finish the interview. The payment card method consists in listing possible values of WTP on a card and showing them to the interviewee, who should choose the payments that correspond to her willingness to pay. The dichotomous choice method consists in a first question about voting yes or not for a public program on environmental good and then a second question on the willingness to pay for a precise amount. The second question (follow-up question) is about an amount greater or lower than the one used for the first question, creating in this way a bounded choice. This second approach is a double-bounded dichotomous choice, first proposed by Hanemann (1985). It has been proven that the statistical power of the double-bounded approach is greater than the one with just one choice (Carson and Hanemann 1993).

One of the most important criticisms of contingent valuation studies comes from Hausman et al. (1993), who states that there are basically three kinds of problems with the application of those studies. The first is a bias in the sense of overstatement of values for willingness to pay; the second is a large difference between willingness to pay and willingness to accept; and the third is the problem of embedding which encompasses the scope test (Hausman et al. 1993). The first problem is due to the fact that many times the interviewees don't have market experience and respond without a real perception. Another possible cause is the fact that the interviewees very often want to please the interviewer, or because the nature of the survey that many times let the respondents believe something that is not true. One solution should be to find an adjustment parameter for the willingness to pay, but as the author observes is very difficult to adjust the WTP for a generally accepted parameter. The second problem is about the differences between WTP and WTA. The theory suggests that these two measures must be similar, but many times instead authors find disparities (Hausman et al. 1993).The third problems: scope and embedding, is the most relevant challenge for CV studies. The problem is related to the scope, where respondents to surveys must be willing to pay more for a larger effect than a subset of that effect. There are several studies that apply the scope test, but they do not provide sufficient information to judge an adequate variation in scope. Furthermore, several studies do not provide information for a test implemented by Diamond and Hausman (1994), called "adding-up test," where a group of interviewees is asked the WTP for a good X, another group for a good Y, and a third group for the good X + Y. The result must be that the WTP for the third group must be equal to the sum of the WTP of the first and the second groups. The author states that even if a CV study passes the adding-up test, there might persist non-coherent or non-stable individual preferences.

To try to best predict the willingness to pay and or to accept in our study and possibly overcome some of the problems stated above, we propose to make a "double-bounded" question for the WTP of the preservation of local environment, local culture, and local economy in both the tourists' and the rural household surveys. To avoid the problem of overstatement, we propose to formulate the question in a precise manner on a possible program on environmental, cultural, and economic development and check whether the respondent is favorable or not to be involved in at least one of its components by spending a certain amount of money. A second question with a proposal of a different amount will be also asked to create the double bound. This second question would concern the way (tax, voluntary contribution, user fee) that the interviewee would prefer to exercise her WTP.

To address the embedding problem, we propose to ask a further question at the end of the questionnaire for each interviewee on her willingness to pay for a development program, including all three issues regarding environmental conservation, local culture, and local economic development. To test the embedding problem, we expect that the WTP for these last set of questions should be greater than the first set of questions on WTP, since the latter include just one of the three topics of the development program.

21.5 The Elements of a PES Design: Identifying Capabilities and Options

Capabilities and options are abstract concepts and can be difficult to understand and apply in specific cases. They can be used as the main components of relevant scenarios only if their definition comes from the stakeholders involved. The reasons for constructing scenarios by interacting with the stakeholders are several. First, defining who the stakeholders are, and what is their degree of participation and empowerment, is already a way to find an effective first boundary for the PES design. Second, because contingent wealth relates to property or access rights of specific agents, or sets of agents, scenarios that are predicated on capabilities and options can only be defined in terms of these agents. Third, stakeholders are defined as agents who may hold claims against the PES in question. Once identified, they may have the most interesting and useful knowledge to design the PES itself, as well as on the surrounding environmental, historical, and political conditions. Finally, the interaction of the analyst with the stakeholders and among the stakeholders, with the analyst acting as a facilitator, may generate new valuable information and awareness on the PES potential and on the options open to the stakeholders themselves.

Identifying the stakeholders is an important step in PES design. In general, stakeholders will include various government ministries and bureaus, as well as possible beneficiaries, both positive and negative, of the PES program in question. On the one hand, the number of stakeholders should be as small as possible, as the boundary of the analysis should be defined by the immediacy and the relevance of the claims actually or potentially held against the PES examined. On the other, this should not deter the analyst from choosing a panel of agents, who may have something to say because they represent, in a more general way, the interests involved. In this respect, the choice of stakeholders should incorporate the Delphi technique, which is based on the idea that experts and representatives of the civil society should be consulted to define future scenarios. Representatives of important economic, environmental, and cultural sectors should thus be consulted and their opinion and views checked through an interactive and iterative process, until a consensus is reached on a scenario or a range of scenarios.

The aim of the field survey is thus to investigate the conservation of biodiversity, local culture, and economic development through the promotion of PES as alternative forms of economic activity and local community engagement. The **overall objective** of the study is twofold: (1) *to promote and strengthen models of integrated natural resource management with the activation of PES;* (2) *to improve the socioeconomic development of local communities in Azerbaijan and biodiversity conservation*. By evaluating the potential for PES and other forms of environmentally friendly associated economic activities in some of the most disadvantaged regions of Azerbaijan, the study will also contribute to better knowledge on rural economic diversification and job creation, especially involving women and youth. The overall objectives can be divided into five components:

1. *Reinforcement of the institutional, strategic, and legal framework for the management of natural resources, developing a regional and local PES strategy to promote integrated management of agriculture, forestry, and conservation.* With the analysis of secondary data, the already existing legal framework, and by interviewing institutional expertise, the project aims to improve the institutional framework of PES development by policy purposes and strengthen the practices of national protected areas.
2. *Building local capabilities for sustainable land management and biodiversity conservation with an integrated natural resource management approach, such as strengthening the training and capacity of different stakeholders for environmental management, environmental education, and related jobs, especially directed to local communities.* The questionnaires administered through the survey will elicit the degree of knowledge about conservation activities and best practices for capacity building and skills development, for environmental and biodiversity preservation.
3. *Analyzing investment priorities in the management plans through the provision of goods and civil works, including the construction of information kiosks, lodging for staff, clearing of footpaths, and soil and water conservation management*
   From the analysis of secondary data and the administration of the questionnaires, the project aims to identify the lack of infrastructure for environmental management (EM) and suggest priorities for investment that may enable PES and other market-friendly EM systems. In this context, central and local government agencies will be involved to provide policy indications to improve farmers' market accessibility and job prospects for the local population.
4. *Investigating the potential for community-based programs for the environmental management based on PES*
   Not only there will be a focus on improving job situation for local population but also the involvement of the communities on the decision process for improving the management of environmental resources and cultural preservation through PES and other market-friendly policy programs.
5. *Measuring the total economic value of biodiversity in regional sites, its use and non-use values, willingness to pay and willingness to accept for ecological services, and environmental preservation*
   The evaluation of the environment is fundamental to enable social and economic policies for sustainable development. In this context, the survey aims to better understand the total economic value of the biodiversity in the project area and identify different options by enabling a set of future choices to strengthen the capabilities of the local population to manage the environment under present and future pressures which can undermine their well-being.

All these components are functional to a sustainable development of a PES system, aimed at the conservation of the environment, local culture, and economic development of the local population. This can be monitored by analyzing different data and set of variables which can be categorized as follows:

1. **Conservation of ecosystem and cultural heritage.** These variables are functional to check the status of the natural goods and services around the local communities and the possibility to improve the health of the flora, fauna, and avifauna. Furthermore, the investigation will focus on cultural issues and in particular on the status, popularity, and importance of local culture, including food and handicraft, and the preservation of the culture trough, the education of the youth. The investigation on these variables will be done through interviews based on questionnaires administered to households on their perception of environment and cultural issues in the region. Further questions will be directed to visitors and tourists on the preference for environmental and cultural good and services, to check the possibility to develop them in the ecotourism context and finally with interviews with institutional experts on policies and projects in the field of tourism, ecotourism, biodiversity, and infrastructure.
2. **Wealth conditions.** These components concern the living/economic conditions of the local populations, including the availability and creation of new jobs, the number of women and men entrepreneurs, the equity in sharing environmental benefits/costs, and the impact of different models of environmental management and economic activity on reducing poverty and increasing social inclusion.
3. **Enabling environment for ecotourism promotion**. These variables aim to investigate suitable environments for the development and management of alternative tourism, including institutional capacity, infrastructure, and skilled manpower. The investigation will also focus on the attitude of the local population to develop ecotourism activities and operation, as well as tourists' preference for ecotourism experiences. In this context, a part of the questionnaire addresses ecotourism preferences of both households and tourists. The questionnaire directed to business managers, instead, will focus on infrastructure and capacity for tourism activities, as well as on the implementation of ecotourism operations.
4. **Tourist satisfaction.** This part is fundamental to investigate tourists' attitudes toward ecotourism opportunities, including the analysis of the willingness to pay for ecotourism activities which might represent a source for community development and preservation of biodiversity and cultural heritage. The tourist questionnaire will aim to investigate these variables, including positive feedbacks and complaints, as well as perception of safety in tourism sites.
5. **Participation awareness**. This component concerns the effectiveness of alternative PES schemes in terms of total economic benefits for the community, their distribution, and their social and cultural effects. The study will also focus on the participation of local communities to the decision process, including the number of meetings for planning common activities.
6. **Option values.** We can distinguish four types of option values that will be investigated by the survey: (a) OV (option value proper). This is a form of risk

premium that arises from the fact that individuals are willing to pay more for a given resource if there is uncertainty on its future availability, (b) QOV (quasi option value). This value arises from asymmetric irreversibility and may be positive if by not acting now an irreversible change in the environment is avoided, but it can also be negative if the resource may be irreversibly lost or damaged in the future. (c) QOV is also the typical value considered in real options on a project (ROOs), and depends on the faculty of delaying the project or one or more of its components. While the action of "not adopting the project now" can be reversed in the future, in fact, the action of "adopting" is irreversible in the sense that the resources committed cannot be recovered (in all or in part). (d) Real options in a project (ROIs), finally, are the options that are created as both planned and unplanned (and perhaps unintended) consequences of the project. These are the flexibility options that can be exploited by project management, or the options to expand, to contract, to exit, to suspend operations, etc. that have received most attention in the business management literature (Knudsen and Scandizzo 2002; Knudsen and Scandizzo 2005a, b; Cicchetti and Freeman 1971).

21.6 Structure of Questionnaires and Interviews

The field study is based on surveys articulated in sample data collection through two semi-structured questionnaires and in one set of more informal interviews. The questionnaires address, respectively, local households and tourists. The informal interviews are directed to institutional experts and operators.

The questionnaires for tourist and local households is mainly composed of closed questions, in order to facilitate the task of the interviewers and because of time constraints. In this manner, the interviews tend to be quicker to administer and easier to analyze, even though they tend to have also drawbacks such as the fact that the respondents cannot raise new issues during the interview, so that relevant and interesting information could be lost. To avoid this risk, the questionnaires will be semi-structured and a question on whether the interviewer wanted to add something on the issue will be included at the end of each questionnaire.

Interviews with institutional experts will be made by open questions to capture and analyze the experience and suggestions from people who know the present situation in the field and can contribute to find solutions for the development of PES systems.

The structure of the questionnaires will consist of four parts:

1. **Common section**. The first section will ask questions about demographic and socioeconomic data to check the profile of the people that could be involved in PES activities. This section is important for underlying drivers of individual preferences and decisions around the use and consumption of good and services. The information contained in this section is useful and functional to specific *hypotheses,* because it will be able to point out the interaction between the stakeholders at all levels and the already existing structure of agriculture and

related activities, such as current capital asset and services. With the stakeholder profiles, we will be able as well to elicit first set information on the status of the development of local communities such as job situation, economic condition, and source of income for the households. The information needed at this stage is basic information on age, gender level of income, and type of job.

2. **Present situation.** This section is useful to check the present situation of the environment and development of local population and business. It is important to identify different PES development opportunities, strengthen the services already implemented for the environment in general, and for activities leading to eco-tourism. This section includes data collection on the present level of consumption and production of environmental services for the local population, government officials, visitors, and tourists.
3. **Knowledge and attitudes.** The aim of this section is to analyze target group knowledge and attitudes on eco-management activities and their potential benefits for the conservation of the environment, cultural heritage, and sustainable development. This section is important to calibrate possible PES and related policies for tourism and infrastructure and marketing strategies of local business. Questions will investigate the interest of different interviewees on environmental and cultural issues and their attitude toward environmental legislation. This type of questions, together with those on the willingness to pay/accept, can also contribute to identify the determinants of consumption choices of environmental services in a context of rationality, on the basis of private cost and benefits, or, alternatively, to maximize common interests.
4. **Willingness to pay/accept payment.** This section aims to analyze the "stated preferences" of local population to accept payment for environmental services. It aims also to investigate the willingness to pay of tourists and visitors (both present and potential) for the consumption of ecotourism services and for the conservation of cultural and natural heritage. The section is important to inquire on the feasibility and possible financing needs of PES as well as policies for the sustainable economic development of the local population. It is also important to obtain estimates of parts of the total economic value for ecosystem services, especially the contribution for non-use value. The rationale of this section is to point out the sensitivity of the interviewees with respect to environmental issues, provide indications for policies and financing sources on cultural and economic issues in the context of ecotourism management. Willingness to pay/accept measurements will also be instrumental to estimate the total economic value of ecosystem services. The set of questions on WTP will be made to both tourists and local population for the use and preference of ecosystem services and natural resource preservation.

The survey was presented to respondents as part of a PES project to WTP/A of ecosystem service seller and buyers. Offered ecosystem services include water, forest, pasture, and recreational values. These provided services are offered to downstream water users and potential tourists (buyers) who would pay for conservations of environmental values. Environmental benefits should include increased recreational activities, increased water uses, esthetic enhancement, biodiversity support, and conservation of forest and grassland landscapes. Other benefits would concern health, life expectancy, agriculture, and recreational fishing. Prevention of erosion, landslides, flash floods could also be counted as benefits. Potential sellers include local communities and farmers who intensively use forest and pastures in upstream regions. As providers of ecosystem services, these people constitute the stakeholders who should accept payments.

The following questionnaires were designed and pretested:

- A tourist WTP questionnaire was administered to tourists who would pay for recreational values (forests, streams, fishing, hiking, esthetic view) in the target region.
- Downstream water users' WTP questionnaire. Because the forests and pastures are the main regulators of small streams, which serve as the main water sources for downstream users, downstream users should be interested in paying for better water services from these ecosystems.
- Upstream community WTA questionnaire. Upstream communities are the main users of ecosystem services that create many obstacles for downstream water users and tourists. For example, land degradation may reduce the recreational value of the area. Water wasting or pollution of water sources may also create concerns for downstream water users. Upstream communities may also be PES sellers and could be interested to reduce use of ecosystem services instead of accepting payments.

The survey lasted approximately 2 weeks. A total of ten enumerators and one tabulator were involved in the process with an average number of 30 questionnaires filled by each enumerator. The questionnaires completed were 304. The number of filled questionnaires for each type was as follows:

- Questionnaires for upstream communities, 50.
- Questionnaires for forest and pasture users 50.
- Questionnaires for downstream water users 50.
- Tourist questionnaires 98.

Main areas through the target region were identified:

(a) Brovdal and Lahij villlages of Ismailli district and Archiman and Gonagkend villages of Shamakhi district. This area includes the main upstream region, where forests and pastures occupy land surface. Small streams, nice landscape views are in these areas. These are the areas, where upstream communities live. WTA was evaluated during surveys. Questionnaires for forest and pasture users were also filled in this area. Pasture users' questionnaire was mainly filled in Brovdal village of Ismailli district, the local people of which mainly use pastures.

(b) Ranjbar and Navahi villages of Hajiqabul District, Agbula village and Arabsartan and Gasimbeyli villages of Ismailli district.

Firstly, the survey was conducted in the upstream villages. Each questioning round lasted approximately 20 min. In most cases, enumerators spent more than additional 10 min to explain the purpose of the survey. Most of the responders showed high interest and, in many cases, interrupted asking additional questions in their turn. This increased the time of the application of one questionnaire up to 1 h, but it was productive since it showed the interest and concern of responders. Below we give a more extensive description of the survey processes.

Upstream community WTA survey. Survey was taken mainly from local community members. Responders have various income sources. Local teachers, medical workers, municipality members, (who are part-time farmers also), farmers were main responders during the survey. These people are the main water users in the region. The interest in the survey in both districts (Ismaili and Shamakhi) was very high.

Pasture users' WTA survey. The pasture users' survey was taken mainly in the Brovdal village of the Ismailli district. Some of the questionnaires (15) were filled in the Archiman village of the Shamkhi district. Brovdal is a most remote area of the target region. It has extensive pastures which have problems related to land degradation and overgrazing. Local people prefer to use summer pastures early that cause severe land degradation. The area is attractive with its landscapes and hiking areas that could be used by visiting tourists. In addition, some attractive summering areas could be used for long time stays for camping. In addition, forests are the main regulators of water resources. Forests also provide provisioning services that include regulatory services (maintaining of water quality, buffering of floods) and cultural services (recreation and tourism). Natural regulation of streams and option values increase total value of local landscapes. After explaining importance of local landscapes, enumerators started the survey process. In most cases, there was high interest in the survey.

Downstream water users' WTP survey. The downstream water users' survey was taken in downstream areas of the Pirsaat and Girdmanchay rivers of Azerbaijan. Enumerators involved four downstream communities into the survey. Two villages of the Hajigabul village are located in the downstream part of the Pirsaat river. These are the villages of Ranjbar and Navahi, the only water source for which is Pirsaat River.

21.7 The Econometric Model

We start with the standard Random utility model (RUM) (Marschak 1960; McFadden 1974; Hanemann 1984; Train 1986; McFadden 2001), where the household maximizes its utility and whose indirect utility function is:

$$V = V(p, q, y) \tag{21.1}$$

where p represents the market price vector of commodities, q is the status of the commodity (in this case the status of the biodiversity of the state), which assumes a value of q_0 for the status quo and q_1 for the improved situation of the biodiversity; and y is the income of the household. The Hicksian compensating variation for the household's value change is (McFadden 1999):

$$V(p, q_1, y - C) = V(p, q_0, y) \tag{21.2}$$

The improvement of the biodiversity services from q_0 to q_1 would improve household utility; hence C would be a positive measure and represents the Willingness to Pay (Train 2001), Train and McFadden (1978):

$$V(p, q_1, y - WTP) = V(p, q_0, y) \tag{21.3}$$

which is the maximum amount the household is willing to pay for the improvement in the biodiversity preservation from q_0 to q_1.

If the respondents are asked whether to pay an amount C for the conservation of biodiversity, obtaining the amount q_1, her answer would be yes if the following condition holds (Hanemann 1984):

$$\begin{aligned} \Pr(yes) &= \Pr(P, q_1, y - C, Z) + \varepsilon_1 \geq V(p, q_0, y - 0, Z) + \varepsilon_0 \\ &= \Pr(P, q_1, y - C, Z) - V(p, q_0, y - 0, Z) + \varepsilon_1 - \varepsilon_0 \geq 0 \end{aligned} \tag{21.4}$$

where ε_0 and ε_1 are components of utility that cannot be observed and are identical and independently distributed (i.i.d.)

If we define
$\Delta V = \mathrm{V}(p, q_1, y - C, Z) - V(p, q_0, y - 0, Z)$ and $\gamma = \varepsilon_1 - \varepsilon_0$, we can then write:

$$\Pr(yes) = \Pr(\gamma \geq -\Delta V) = 1 - F\gamma(-\Delta V) = F\gamma\Delta V \tag{21.5}$$

where $F\gamma$ (ΔV) represents the cumulative density function (cdf) of the respondent's true maximum WTP. This model can be estimated by maximum likelihood methods. Let R_k be an indicator variable for observation k, with:

$$\Pr(yes) = \Pr(R_k = 1) = \Pr(\gamma_k \leq \Delta V_k) = F\gamma(\Delta V_k) \tag{21.6}$$

$$\Pr(No) = \Pr(R_k = 0) = \Pr(\gamma_k \leq \Delta V_k) = 1 - F\gamma(\Delta V_k) \tag{21.7}$$

The dichotomous CV technique estimates the mean and median WTPs based on the coefficients related the WTP responses against a constant and the bid (BID). Additional coefficients (X) of other variables like responses to attitude questions or the respondents' demographic information may also be factored into the model. In this study, the linear log-probit model was employed to analyze the dichotomous choice format of the contingent valuation method. This specification assumes that:

$$\Pr(Yes) = F\gamma(\Delta V) = \exp(\alpha + \beta_1 BID + \beta_2 X + \varepsilon) \tag{21.8}$$

where ?~*i.i.d.N* 0, σ2 or equivalently:

$$\ln(F\gamma(\Delta V)) = (\alpha + \beta_1 BID + \beta_2 X + \varepsilon) \tag{21.9}$$

Where α and β are coefficients to be estimated and BID is the amount of given money the respondents were asked to pay. The corresponding likelihood is:

$$logL = \Sigma_k\{R_k F\gamma(\Delta V_k) + (1 - R_k) * \ln(1 - F\gamma)(\Delta V_k)\} \tag{21.10}$$

In this case of the lognormal specification, the conditional mean and median WTP are calculated as follows (Haab and McConnell 2002):

$$MeanWTP = E[\exp(\alpha + \beta_1 BID + \beta_2 X + \varepsilon)] = \exp\left(-\frac{\alpha + \beta_2 X}{\beta_1 + (\sigma^2/2)}\right) \tag{21.11}$$

$$MedianWTP = \left(-\frac{\alpha + \beta_2 X}{\beta_1}\right) \tag{21.12}$$

As explained in the previous section, in this study, we have applied the *double-bounded model*, where a follow-up question has been asked to the respondent after the answer to the first question. If the answer to the first question was positive, then the second bid was the double of the first. If the answer to the first amount was no, on the other hand, the second bid was the half of the first. In such double-bounded dichotomous choice model, the willingness to pay can be estimated either with interval data analysis or by the seemingly unrelated (SURE) model (Cameron and Quiggin 1998). With these models, the bound on the WTP depends on the first and second answers:

WTP $\geq$ bid2 if the responses are yes and yes.
bid1 $<$ WTP $\leq$ bid2 if the responses are yes and no,
bid2 $<$ WTP bid1 if the responses are no and yes,
WTP $<$ bid2 if the responses are no and no.

For the yes yes responses, the probability is:

$$\Pr(y_{1i} = 1 \; and \; y_{2i} = 1 | x_i) = \Phi\left(\frac{x_i\beta}{\sigma} - \frac{bid_2}{\sigma}\right)$$

For the yes and no responses, the probability is:

$$\Pr(y_{1i} = 1 \; and \; y_{2i} = 0 | x_i) = \Pr(bid_1 < WTP < bid_2)$$
$$= \Phi\left(\frac{x_i\beta}{\sigma} - \frac{bid_1}{\sigma}\right) - \Phi\left(\frac{x_i\beta}{\sigma} - \frac{bid_2}{\sigma}\right)$$

For the no and yes responses the probability is:

$$\Pr(y_{1i} = 0 \; and \; y_{2i} = 1 | x_i) = \Pr(bid_2 < WTP < bid_1)$$
$$= \Phi\left(\frac{x_i\beta}{\sigma} - \frac{bid_2}{\sigma}\right) - \Phi\left(\frac{x_i\beta}{\sigma} - \frac{bid_1}{\sigma}\right)$$

For the no and no responses, the probability is:

$$\Pr(y_{1i} = 0 \; and \; y_{2i} = 0 | x_i) = \Pr(WTP < bid_2) = 1 - \Phi\left(\frac{x_i\beta}{\sigma} - \frac{bid_2}{\sigma}\right)$$

where Φ(.) denotes the standard cumulative normal distribution function. We can estimate this model either by solving the maximum likelihood function, estimating β and σ, or by estimating the probit model using x_i and bid_i as explanatory variables. We use the latter approach and obtain the estimate of β/σ, associated to each explanatory variable and − 1/σ associated to the bid coefficient, after estimating the probit model. The error terms ε_1 and ε_2 are assumed to be normally distributed with mean zero and variances σ_1 and σ_2, and to have a bivariate normal distribution with correlation coefficient ρ. Given these premises, the mean WTP value can be estimated as E(WTP) = $\bar{x}\widehat{\beta}$, where x represents a vector of simple averages of independent variables (Cameron and Quiggin 1998).

The problem with this approach is that intuitive restriction on WTP according to economic theory are not incorporated, such as the fact that WTP should be positive and reasonably contained within a range that cannot be greater than family income. We can incorporate these restrictions, however, by estimating a model that assumes an exponential WTP: $\mathbf{WTP = e^{x\beta + \varepsilon}}$, and thus permits only positive WTP values. In this case, the bid variables are replaced with the log of bid, i.e., bid_i is replaced with ln (bid_i) for $i = 1, 2$ and median and mean WTP are respectively:

$$Median \; WTP = e^{\widehat{x\beta}} \tag{21.13}$$

$$Mean \; WTP = e^{\widehat{x\beta} + 0.5\widehat{\sigma}^2} \tag{21.14}$$

21.8 Results

Because estimates of WTA are key to an effective PES program, the results of the survey were used to investigate the possible relationship between people's availability for PES participation and a number of socioeconomic variables. Among these, three main covariates emerged from the econometric estimates: income (four classes) and education (two classes) and gender (1 male, 2 female). Tables 21.2–21.6 below show preliminary econometric results for upstream communities and three (PES) typologies: (a) willingness to accept payment (WTA) for conserving and delivering water to downstream users (Table 21.2), (b) WTA for conserving forests and, (c) WTA for conserving pastures. The results suggest three main hypotheses:

1. WTA has a robust and significant constant component which hovers between 200 and 300 manat per ha.
2. The income variable is always significant with a large and positive effect on the WTA.
3. Both education and gender are weakly significant (perhaps for the small number of observations), with more educated people and males desiring higher payments.

21.9 Conclusions

The study presents an approach to PES design based on econometric analysis of willingness to participate using a direct survey of potential beneficiaries. The survey itself demonstrated the feasibility of collecting fast and accurate information in the field prior to the enactment of such a scheme. Because PES is an original form of contractual relationship in which the government acts as a sort of reverse concessionary and the private sector as the grantor of rights, it is important to explore the willingness to accept (WTA) such a relationship from the private parties potentially interested and the variables that determine or condition higher or lower WTA values

Table 21.2 Willingness to accept payment to conserve water to be provided to downstream users

Dependent variable: WTAU1				
Method: Least squares				
Date: 12/11/16 time: 04:25				
Sample (adjusted): 1 22				
Included observations: 18 after adjustments				
	Coefficient	Std. error	*t*-Statistic	Prob.
C	329.9427	141.4692	2.332259	0.0351
EDUC	1.049618	43.95386	0.023880	0.9813
GENDER	−71.83206	55.78467	−1.287667	0.2187
YEARLY	36.33588	17.99773	2.018914	0.0631
R-squared	0.335321	Mean dependent var		318.6111
Adjusted R-squared	0.192890	S.D. dependent var		61.28059
S.E. of regression	55.05407	Akaike info criterion		11.04764
Sum squared resid	42433.30	Schwarz criterion		11.24550
Log likelihood	−95.42875	Hannan-Quinn criter.		11.07492
F-statistic	2.354265	Durbin-Watson stat		1.832726
Prob(F-statistic)	0.116084			

Table 21.3 Willingness to accept payment to participate in a conservation program per ha of forest

Dependent variable: WAPF1				
Method: Least squares				
Date: 12/11/16 time: 07:20				
Sample (adjusted): 1 28				
Included observations: 23 after adjustments				
	Coefficient	Std. error	*t*-Statistic	Prob.
C	273.0880	82.87297	3.295260	0.0038
EDUC	22.51092	29.37980	0.766204	0.4530
GENDER	−53.00686	31.40832	−1.687669	0.1078
YEARLY	33.80536	15.64589	2.160655	0.0437
R-squared	0.318761	Mean dependent var		309.7826
Adjusted *R*-squared	0.211197	S.D. dependent var		60.92988
S.E. of regression	54.11462	Akaike info criterion		10.97686
Sum squared resid	55639.46	Schwarz criterion		11.17433
Log likelihood	−122.2339	Hannan-Quinn criter.		11.02652
F-statistic	2.963452	Durbin-Watson stat		2.144860
Prob(F-statistic)	0.058212			

Table 21.4 Willingness to accept payment to conserve per ha of pasture

Dependent variable: WAPFUP1				
Method: Least squares				
Date: 12/11/16Time: 07:26				
Sample (adjusted): 1 26				
Included observations: 20 after adjustments				
	Coefficient	Std. error	*t*-Statistic	Prob.
C	226.9381	108.3649	2.094202	0.0525
EDUC	23.61239	37.04127	0.637462	0.5328
GENDER	−40.81422	35.34705	−1.154671	0.2652
YEARLY	45.29817	18.36478	2.466578	0.0253
R-squared	0.353971	Mean dependent var		302.0000
Adjusted *R*-squared	0.232840	S.D. dependent var		66.00239
S.E. of regression	57.80995	Akaike info criterion		11.12906
Sum squared resid	53471.85	Schwarz criterion		11.32820
Log likelihood	−107.2906	Hannan-Quinn criter.		11.16793
F-statistic	2.922226	Durbin-Watson stat		2.135442
Prob(*F*-statistic)	0.065918			

across heterogeneous agents. The results suggest that positive attitudes towards market-friendly schemes are widespread across potential participants. WTA levels depend on key variables such as incomes, information, and gender, but basic levels tend to be high regardless of these variables. This in turn indicates that the key element of willingness to participate are already present in the population interested

Table 21.5 Willingness to accept payment to participate in a conservation program per ha of forest (ordered probit)

Dependent variable: WAPFUP1				
Method: ML – ordered Probit (Quadratic hill climbing)				
Date: 12/11/16 time: 08:46				
Sample (adjusted): 1 26				
Included observations: 20 after adjustments				
Number of ordered indicator values: 5				
Convergence achieved after 5 iterations				
Covariance matrix computed using second derivatives				
	Coefficient	Std. error	*z*-Statistic	Prob.
EDUC	0.584619	0.714547	0.818167	0.4133
GENDER	−0.715095	0.663003	−1.078570	0.2808
YEARLY	1.060659	0.441259	2.403712	0.0162
	Limit points			
LIMIT_225:C(4)	0.134414	2.153863	0.062406	0.9502
LIMIT_295:C(5)	1.393285	2.140351	0.650961	0.5151
LIMIT_350:C(6)	2.165017	2.124662	1.018994	0.3082
LIMIT_450:C(7)	4.480160	2.452594	1.826703	0.0677
Pseudo R-squared	0.161018	Akaike info criterion		2.980751
Schwarz criterion	3.329258	Log likelihood		−22.80751
Hannan-Quinn criter.	3.048784	Restr. log likelihood		−27.18473
LR statistic	8.754440	Avg. log likelihood		−1.140376
Prob(LR statistic)	0.032740			

Table 21.6 Willingness to accept payment to participate in a conservation program per ha of pasture (ordered probit)

Dependent variable: WAPFUP2				
Method: Least squares				
Date: 12/11/16 time: 07:28				
Sample (adjusted): 1 26				
Included observations: 13 after adjustments				
	Coefficient	Std. error	*t*-Statistic	Prob.
C	183.8889	90.92838	2.022349	0.0738
EDUC	11.66667	28.42578	0.410426	0.6911
GENDER	−41.66667	24.24158	−1.718810	0.1198
Ad YEARLY	61.11111	23.55858	2.594006	0.0290
R-squared	0.540881	Mean dependent var		253.4615
Adjusted R-squared	0.387842	S.D. dependent var		46.47511
S.E. of regression	36.36237	Akaike info criterion		10.27261
Sum squared resid	11900.00	Schwarz criterion		10.44644
Log likelihood	−62.77194	Hannan-Quinn criter.		10.23688
F-statistic	3.534260	Durbin-Watson stat		3.507094
Prob(F-statistic)	0.061450			

and that future application of PES schemes are likely to meet with general consensus. Even though they present implementation challenges because of their innovative design and lack of previous experience of both private and public parties, PES appear thus to have good chances of succeeding because of the attitude of the potential participants. By creating market-based mechanisms for environmental protection, which can potentially spread to many sectors and areas of the country, they thus appear to be a good choice to steer public policies and private behavior toward more sustainable management systems of natural resources.

Annexure: Potential PES Schemes for the Target Region

PES Scheme 1: Grassland Protection Grant Scheme

Buyer: Government of Azerbaijan (or UNDP at the pilot stage)

The PES scheme aims to improve management of private and municipality lands and increase public benefits derived from existing mountain landscapes and invest in improving ecosystems for additional public benefits. The grant scheme covers only municipalities and registered private landowners. According to this scheme, municipalities and registered landowners will apply for the grants. These grants include regular payments to landowners for a given time. Landowners take an obligation to manage their lands properly. In the application, landowners will be required to identify their intentions and commitments with respect to future management and agree on land use forms and procedures. For example, the grantee can commit to conserve and manage private forest in his/her land. Also, by applying for the grant, municipalities will openly develop their future plans with respect to future land use. For example, they can commit to protect and use as forest area a certain land area. Alternatively, on behalf of the municipalities, Pasture Users' Associations may develop a participatory land management plan, according to which, land will be managed properly, and natural habitat is conserved. Local landowners will join into FUAs or PUAs and apply for grants.

Sellers: Sellers include all the registered landowners and municipalities in the selected area of the target region. They will apply for grant support and accept agreement before they will start the project. Relevant government bodies (or UNDP at the initial stage) will administer grants.

Type of ecosystem services provided: This scheme targets protection and management of municipality lands, which will provide clean water, reduced risk for floods, recreational use, and esthetic and existence value. Improved soil quality will contribute to restoration of vegetation cover. Touristic activities in the area will be intensified.

PES Scheme 2: Establishment of a National Ecosystem Foundation

In order to improve management of private and municipality lands and increase public benefits derived from existing mountain landscapes, a National Ecosystem Foundation (NEF) may be established. NEF will be a public body that will work in the whole country, including the target region. Recreational hunters, tourists, berry and mushroom gatherers will be the direct users and buyers of the NEF-sponsored services. Water users, and other persons willing to pay for existence and option values are counted as the indirect users. All the people that are interested in ecosystem protection or protection of species and are ready to pay can be counted as the indirect beneficiaries. Main income of the NEF will be donations of the potential buyers. Simultaneously, NEF may receive support of international and national donors.

Sellers: Sellers include all the registered landowners and municipalities of the target region. They may apply for the support of NEF or NEF will offer its support to them. Registered landowners or municipalities will sign detailed agreement on payments.

Type of ecosystem services provided: Clean water, reduced flood risk, esthetic values, existence values, option values, bequest value, recreational services will be provided to buyers. Increased touristic activities will give a stimulus to increase donations in the future.

Willingness to pay: Survey is important to assess willingness to pay of people looked over as potential buyers.

PES Scheme 3: Direct Government Support

Buyer: Government of Azerbaijan (or UNDP at the pilot stage)

Seller: Local landowners

The buyers would like to shield or remove environmentally sensitive land from use. Planted plant species will improve resistance of land and increase quality of ecosystem services. Landowners will receive annual rental payments from the government. Contracts for land enrolled in this scheme are 10–15 years in length. The long-term goal of the activity is to reestablish valuable land cover to help improve ecosystem services and quality of environment, prevent land degradation.

Sellers: Sellers include all the registered landowners and municipalities of the target region. In order to be enrolled in the program, they will apply for government support. Their PES contracts will typically last10–15 years.

Type of ecosystem services provided: Clean water, reduced flood risk, esthetic values, existence values, option values, bequest value, recreational services will be provided by sellers. Improved lands will provide water that mitigates the impact from debris flows and services that increase water-producing ability of landscapes. PES are equivalent to money transfers.

PES Scheme 5: Ecosystem Subsidies

Buyer: Government of Azerbaijan (or UNDP at the pilot stage)

Seller: Local landowners

Subsidies represent money transfers across economic sectors. They lay the groundwork to make the most vulnerable economic sectors to compete with other sectors and to internalize external effects of private production. PES in the form of direct subsidies can be used to support farmers to change their land use patterns in ways that would enable to protect ecosystems. In most of nature conservation programs, governments support farmers with subsidies to convert erodible lands into sustained agricultural ecosystems that are supported by environmentally friendly activities.

In these schemes, landowners are supported by targeted subsidies. Rather than choosing activities on the basis of perceived profits, landowners are induced to apply environmentally friendly practices recommended by governmental agencies. For example, farmers may switch from cattle-breeding to beekeeping or apply butter-strip plowing.

Sellers: Sellers include all the registered landowners and municipalities of the target region. In order to obtain the subsidy, they will need to sign a contract with the government agency that will determine the type of the land use activity to implement.

Type of ecosystem services provided: Clean water, reduced flood risk, esthetic values, existence values, option values, bequest value, recreational services will be provided to buyers. The improved lands will provide water that mitigates the impact from debris flows and increase water-producing ability of landscapes.

PES Scheme 6: Water Trade

Buyer: Azersu Joint Stock Company

Seller: Local landowners

As noted before, the Girdmanchay river basin is a big potential water source at its lower fan, with the Kululu water source capable of providing 500,000 people with high quality drinking water. Grasslands and forests have a rather big role in regulating this source. Recently, Azersu Company has been using this water source to supply downstream towns. A PES scheme may aim to improve management of private and municipality lands and increase quality of provisioning ecosystem services derived from existing ecosystems. Potential buyers will pay upstream farmers to improve land use management through changing traditional land use approach. Azersu may also involve downstream water users into the payments. For example, increased payments of water users may give additional means to payments for ecosystem services. Alternatively, part of the payments made by downstream water users could be used to construct sewage treatment sites in upstream residential areas.

Sellers: Sellers include all the registered landowners and municipalities of the target region. In order to be included in the program, farmers will need to make project proposals or accept the land use change scheme proposed by the buyer.

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Awareness and Conservation Program at an Ecotourism Site in Langkawi Island, Malaysia

22

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Abstract

Most ecotourism sites have a mix of natural resources such as forests and water. Hence, it is common for ecotourism sites all over the world to have these two elements. This is due to ecotourists being attracted to forests and water. Consequently, it can contribute to negative impacts to the environment due to ecotourism activities. As a result, every year, cases such as leptospirosis and water pollution occurred at ecotourism sites particularly in Malaysia. Hence, awareness and conservation programs are much needed, for ecotourism operators and tourists in Malaysia. This program will assist tourists to appreciate and have a better understanding about taking care of the environment at ecotourism sites. This study organized a special awareness and conservation program at an ecotourism site on Langkawi Island for university students. The main objective of this study was to foster awareness among the students about the importance of conserving an ecotourism area for the environment. This program also served as an educational opportunity for the students to learn more about the ecosystem functions of the forests and groundwater. Both natural and social science data were conducted to get rich dataset of this study since no proper research had been done at the site before. The result showed that the visitors would become more

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aware about the ecosystem of the ecotourism site after they joined the awareness and conservation program.

Keywords

Malaysia · Langkawi Island · Ecotourism · Tourists · Forest conservation

22.1 Introduction

The tourism industry has contributed more than RM86 billion to the Malaysian economy with 26.1 million tourist arrivals. One of the most important tourism sectors for the country is from ecotourism activities. The Ministry of Tourism, Arts and Culture (MOTAC) has aggressively promoted a few destinations as the country's ecotourism sites such as; Taman Negara, Pahang, Kundasang, Sabah and Sepilok, Sarawak. Nonetheless, the whole of Malaysia has many ecotourism sites or market themselves for that market. One of these sites is Langkawi Island located within the state of Kedah, at the north part of west Malaysia with an area of 478 km^2. This island is the third-largest island by area in Malaysia. The topography varies from flat coastal plains, hilly areas to rugged mountains (Baban and Wan-Yusof 2003) with tropical humid monsoon climate with a mean annual temperature of about 32 °C (24–33 °C). Due to the geographical location of Langkawi close to Thailand, the island has significant similarity with southern Thailand's climate and weather.

Langkawi Geopark was declared as UNESCO Geopark on May 31, 2006 being the first Geopark in Malaysia and in Southeast Asia. A Geopark is a special conservation area with outstanding geological and biological resources (Ismail et al. 2004, 2005). Langkawi Geopark is the most northern Archipelago and a popular ecotourism site for domestic and international tourists. In 2017, the island received 3.5 million tourists and Langkawi Development Authority (LADA) targeted to make the island as among the top 10 island and ecotourism destinations globally (Langkawi UNESCO Global Geopark Gazette (LUGGG) 2018). Hence, LADA has been actively promoting Langkawi as an ecotourism destination, particularly UNESCO Geopark.

Isa, Hasbullah and Nasir (2015) stated that, more tourism agencies and operators like to associate their agencies to ecotourism activities or green tourism activities. In addition, other tourism establishments (e.g., hotel and restaurants) and non-tourism establishments (such as car manufacturer and petroleum companies) are trying to adopt and adapt green practices and technologies in their organizations. Ecotourism and green practices and technologies are similar to each other, but for this study, we are going to focus only on the ecotourism topic. Most scholars use the definition of ecotourism from the person who first coined the ecotourism concept, that is Ceballos-Lascurain, in 1983. Later, (Ceballos-Lascurain 1987, pp. 13–14) he defines ecotourism as "travelling to relatively undisturbed or uncontaminated natural areas with the specific objective of studying, admiring, and enjoying the scenery and its wild plants and animals, as well as any existing cultural manifestations (both past and present) found in these areas." Nonetheless, some scholars prefer to use other names for ecotourism activities, for example, green tourism, nature tourism, responsible tourism, or sustainable tourism. The main distinction between these terms is the motives and ethics behind them. The concept may not be new, but this is an alternative tourism product with more enthusiasm than environmental sensitivity caters for a quieter, nature-loving minority (Stonehouse 1999) with many different backgrounds. Due to that, many ecotourism destinations use multiple strategies to attract diverse markets to their destination as they have facilities and services that meet the requirements of the high, middle, and low-end market. These ecotourism destinations such as Bali, Krabi, Langkawi, Kyoto, and Queenstown use mixed marketing strategies to cater to all types of tourist markets (Isa et al. 2015; see LUGGG 2018). For example, Langkawi is not only known for ecotourism destination but also for duty-free shopping island and meeting, incentive, conference, and exhibition (MICE) markets. However, the primary focus of this article will be on ecotourism sites in Langkawi.

According to LADA, karst can be defined as a landscape of limestone elongated hills and island. Limestone karsts (hereafter referred to as karsts) are sedimentary rock outcrops that consist primarily of calcium carbonate. Most karsts were formed millions of years ago by calcium-secreting marine organisms (e.g., corals and brachiopods) before tectonic movements lifted them above sea level (MacKinnon et al. 1996). In Southeast Asia, karst covers an area of around 400,000 square kilometers (km^2), with geological ages ranging from the Cambrian to the Quaternary (Day and Urich 2000). Malaysia contains no fewer than 800 separate limestone outcrops, ranging from hills tens of meters across to plateaus many square kilometers in size (Wilford 1964). Although, in Peninsular Malaysia, limestone hills occupy only 0.4% of land area (Chin 1977). World Wildlife Fund (WWF)-Malaysia (2016) reported the areas are estimated at 26,000 ha, mostly concentrated in the northern states and 50,000 ha in Sabah and Sarawak. A number of these consist of limestone islands in the Langkawi archipelago, with major outcrops in Kelantan, Perlis, Kedah, Perak, and northern Pahang. Limestone forest normally trees (normally small trees) and/or vegetation growing over limestone hills (karst) mostly found within tropical rain forest regions of southeastern Asia (see Goltenboth et al. 2007).

In Langkawi Island, rapid development in ecotourism leads to uncontrolled land conversion, including on limestone forest. All these activities result in loss of vegetation cover, increased influx of solar radiation, increased risk of fire, desiccation, and the resulting loss of topsoil (Schilthuizen 2004). The existence of vegetation was important for karst ecosystem for its role in absorbing and supplying water in the area. The absence of vegetation would cause insufficient water supply during the dry season (Satyanti and Wahyu 2010). Deputy Minister of Energy, Green Technology and Water, Datuk Seri Mahdzir Khalid said Langkawi's rapid development calls for additional water supply as more hotels, houses, and business premises are coming up. This is because Langkawi has inadequate water supply and may face water scarcity by 2020 (The Malay Mail online 2014). Based on that notion, the main objective of this study is to foster awareness among the students or visitors about the importance of conserving one ecotourism area for the environment. While two specific objectives for this program were to

- Educate the students or visitors about the unique features of the water and forest at an ecotourism site.
- Get the students' or visitors' feedback before and after they participated in awareness and conservation program at an ecotourism site.

22.2 Research Methodology

For this section, the discussion on how this research is undertaken will be presented. Due to lack of data on this topic and based on the objectives of this study, face-to-face interviews were conducted to cover the social science study. While for pure science study, two forest hydrology experts' interactive explanation and a few simple tests using portable electronic pH meter to test the water quality reading at the study site were used. The study chose to do awareness and conservation program on water and forest resources at the chosen ecotourism site in Langkawi Island.

22.2.1 Study Site

The location of the study is at Penarak Nature Centre (PNC) Sdn. Bhd., which is situated about three kilometers to the east of Kuah Jetty, comprise a total land area of 13 hectares (Fig. 22.1). Since the land area of bedrock bared counted for more than 50% of the total area mainly as limestone forest and located close to the Kilim Karst Geoforest Park, this research center has the same rock formation as Setul Formation. Due to the unique geological characteristics, the forest has the highest elevation of about 90 m.a.s.l, where many underground monsoon streams, caves, sinkholes, tufa falls, as well as a rich variety of plants and animals, are found. The size of water catchment area inside PNC is about 2 km^2 where most of the limestone forest was classified as undisturbed forest by Kedah Forestry Department. PNC is home to many types of vegetation such as Melunak (*Tiliaceae*), Minyak beruk (*Xanthophyllum lanceatum*), *Streblus ilicifolius*, wild orchids, mushrooms, and many more. Besides, the limestone forest is the preferred habitat for many bird species, including the white-bellied eagle and Brahminy kites, small mammals such as the Dusky Leaf Monkey, insects, and aquatic lives.

For the first stage of study, on-site visits to gather the needed data at the PNC site were done in February 2019. Based on the first stage visits, a special limestone river conservation program was designed and tested on four key tourism stakeholders in Langkawi. The key stakeholders' comments and suggestion were gathered, and some amendments were done to the program. This was necessary to make sure the program meet the objectives of this study. The actual program involved 50 students

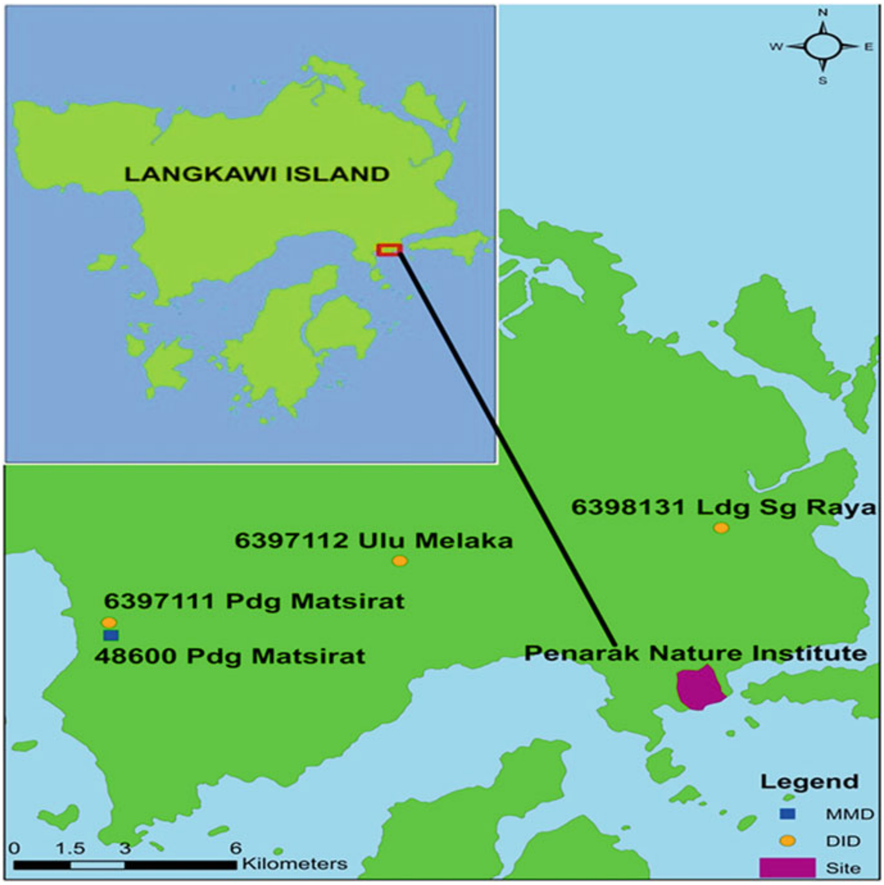

Fig. 22.1 Location of Penarak Nature Center in Langkawi Island

from Universiti Putra Malaysia (UPM) and Queensland University of Technology (QUT), six staff from UPM and four staff from QUT from 23 to 25 September 2019. These students were divided into two groups. The first group were students who had a pure science background, while the second group were students with a social sciences background. All students were asked to prepare a report about their experience, opinion, and suggestion about the program at the study area. While six students from UPM and four from QUT were interviewed to get their feedback about the program. This study also interviewed staff from UPM, QUT, and key tourism stakeholders in Langkawi about the program. Before the visit, both groups were given a briefing and explanation about limestone forest in general by experts from PNC, UPM, and QUT.

22.2.2 River Conservation and Awareness Program

The rivers awareness and conservation program were conducted at PNC limestone area. All participants were transported to the area by speedboat from Penarak jetty since there is no access road to go there. The program can be divided into two parts, the social science and pure science parts as presented below.

22.2.3 Social Science Program

- All participants were required to collect rubbish from the beaches and rivers at PNC site which is known by the locals as Batu Ayam and Batu Orchid. Most of the rubbish usually was washed up from the ocean since its close proximity to nearby Kuah town and is a busy waterway for ferries and ships. Also, rubbish from participants' lunch and drinking bottle were transferred to dumping area provided by the local authorities at Penarak jetty. The reason this activity was part of the education program was to explain to the students about "leave no trace" principle which is significantly important in ecotourism ethic. Also, to instill responsibility among the participants to take care of the environment, particularly at a fragile area.
- **Trekking and Interpretation Activities Along Limestone Forest Trail.** Both groups were taken into the limestone forest by forest trail from Batu Ayam Beach (trail head) to the unique Tufa fall of Batu Orkid, which was located about 300 meters from the trail head. Besides visiting the Tufa fall, they were taken around the limestone forest, to the caves, streams, and had been introduced to some features of limestone forest such as rock formations, sinkholes, vegetation, and wildlife. They were accompanied by a few experts in natural and social science fields. An expert in environmental interpretation gave a briefing and explanation to the students during their forest trekking. The interpretation session covered theory and knowledge about the water resources, geology, vegetation, insects, wildlife, birding, and their role and relationship towards limestone forest and geopark. Also, biodiversity's contribution to ecotourism in Langkawi Island.
- For natural science students, if they do not understand about the social science program, the social science experts, lecturers, and students would assist them (Fig. 22.2).

22.2.4 Natural Science Program

22.2.4.1 Water Quality and Groundwater Study

The stream within PNC was observed before being chosen for on-site water sampling and water analysis using multivariable meter and turbidity meter. It was done by the group with natural science background assisted by a few experts. The stream includes the waterfall, small pools, sinkholes, spring, valley terraces, and other

Fig. 22.2 (**a**) Students from UPM and QUT were briefed by a few experts before and after their trekking activities. (**b**) Students were taken to Batu Orkid tufa fall formation

Fig. 22.3 (**a**, **b**) Students from QUT are taking water quality data and collecting water samples for further data analysis from Zone **a** and Zone **b**, respectively

formations that related to the geoheritage resources. Water quality analysis was conducted on two different zones with stream, where each zone was further divided into five points along the stream within PNC. The zone was selected based on accessibility and water availability since PNC was affected by two different seasons (dry and wet season). Finally, only one point from each zone was selected based on consideration and suitability for preliminary data collection. Several parameters were tested such as Electric Conductivity (EC), Temperature (T), Total Dissolved Solid (TDS), Salinity (S), Dissolved Oxygen (DO) using special water quality test devices. Throughout basic water quality and other scientific tests, the social science students were assisted by the students from natural science background with close observation from the experts and lecturers (Fig. 22.3).

22.3 Result and Discussion

In this section, the result and discussion will be presented into two parts. The first part will discuss according to the first specific objective, followed by the second specific objective. In addition, the answered before and after the field site visit took place will be discussed here too.

22.3.1 Research Objective 1: To Educate the Students or Visitors about the Unique Features of the Water and Forest at an Ecotourism Site

Before the participants went to the study area, they were well briefed by the lecturers from UPM, QUT, and PNC General Manager. Some photographs were also used during the briefing sessions. They also were told about the dos and don'ts at the study site, particularly to take care of the environment and not to harm the sensitive resources there. They also watched a short video on the limestone forest in Langkawi produced by LADA. All of these processes are necessary to give the participants awareness and educate them about the study area and limestone forest in Langkawi, particularly the unique features of water and forest. All participants have experienced with water and forest, but only a small minority of them had visited a limestone area before.

When asked whether the participants know about limestone forest, all of them said they know about it but with only limited knowledge. However, this study found that, a few students and visitors have visited limestone forest in other parts of Langkawi and elsewhere. Thus, they have some knowledge about limestone forest but more as a tourist destination rather than other scientific aspects of it. The briefing and video watching session helped the participants to have better information and refresh their knowledge about the limestone forest in Langkawi. From the video they watched and photos, they could see the beautiful formation and uniqueness of limestone forest in Langkawi. They noticed that, some of the limestone forest features cannot be found elsewhere but only in Langkawi.

22.3.2 Research Objective 2: Get the Students' or Visitors' Feedback before and after they Participated in Awareness and Conservation Program at an Ecotourism Site

After the participants' hands-on experience at study site, participants showed that they are highly aware and appreciate more of limestone forest after the visit compared to just listening and watching information about limestone forest. Majority of the participants commented that they think limestone forest at PNC is beautiful and will be able to attract many visitors, especially those who like nature because of its rich biodiversity. While trekking and interpretation activities are good for visitors, it must be limited to a smaller number to make sure the information can be delivered effectively to everyone. From the students' report, they suggested the area to be open to the public. However, strict rules and regulations must be imposed to the visitors due to the sensitivity of limestone forest. They agreed that through the on-site visits to PNC make them realize the importance of the limestone forest's existence towards the environment and humankind.

They also gained more conservation experiences through cleaning activities near the river and beach besides understanding that everyone should have their environmental responsibilities towards saving water sources from pollutions. Also, this activity teaches them about "leave no trace" practices and principal in outdoor recreation. The social science students from UPM assisted the students from natural science when they had any difficulties in understanding about the social science program.

The participants were given some exposure about water quality and groundwater study at the study site, too. Before the participants visited the study area, they had no clue about water quality and groundwater study except for participants from QUT who are from pure science bachelor program. During the site visit, all participants were taken to a few water sources at the study area and took part in simple water quality and groundwater study assisted by the QUT participants with close observation from the experts and lecturers.

The data at the study site showed that the stream flow, water velocity, and visibility of the river are almost similar for both days. As this study was carried out in September, the water level for the rivers at Penarak remains the same for both days, which was at 0.28 M. According to climate data from the Department of Irrigation and Drainage (DID), Langkawi receives moderate to high volumes of precipitation beginning March to November which indicates wet season with monthly mean rainfall in July being 268.8 mm. Nine parameters are measured: temperature, electric conductivity, dissolved oxygen, salinity, floatable, odor, and taste; meanwhile several tests for groundwater and minerals content will be conducted at the hydrology laboratory soon. The data shows differences in electric conductivity for both days at Zone A and Zone B. The high reading of EC in this study area is mainly because the stream water is from the limestone spring that came out from the fractures of carbonates rocks in Penarak and could be contributed from a high concentration of dissolved solids in the stream. The mineral content release ions into the waters that flow through or over them, where the geology of a certain area will determine the amount and type of ions (Clean Water Team 2004). These ions include sodium, (Na^+), calcium (Ca^{+2}), potassium (K^+) and magnesium (Mg^{+2}).

Besides, the reading of TDS also shows some increase from 0.31 to 0.33 g/L (Stream A), and 0.30 to 0.31 g/L (Stream B) for 2 days in a row. This parameter could support why the EC increases for both zones. As the rainfall increases, the discharge of groundwater from the limestone brings along the nutrients or chemical substances that dissolved in the water.

Furthermore, the rugged and undulating topography in Penarak restricts human activity such as agriculture or tourism, which is beneficial for the water quality of the stream. Both streams also recorded low dissolved oxygen value for both days. As the river flow source is mainly from groundwater, it is naturally low in DO. However, it also tends to reduce the river temperature, which improves the ability of the water to hold oxygen (Minnesota Pollution Control Agency 2009). The temperature of the zones stays almost the same about 26–27˚C which is the mean temperature in this tropical island. Whereas the pH of both streams stayed between 6.5–7.0, indicating neutral water (United States Geological Survey [USGS] 2020) due to undisturbed areas and could also be contributed by the seasonal change (dry season). Based on the pH scale measures, the logarithmic concentration of hydrogen and hydroxide ions are in equal concentration which make up neutral water (University of Massachusetts Amherst 2016) and drinkable for human. Finally, there were no visible floatable materials or debris, or any objectionable odor or objectionable taste observed at the stream.

22.4 Conclusion

Conservation and awareness programs are needed to raise understanding of environmental problems to achieve a more sustainable environment in the future. This can be done via knowledge and culture transfer in order to raise awareness, educate and assist the local community, and ecotourism operators to understand the importance of limestone in Langkawi Island. Among the important practices and principals in ecotourism is to include the local community in tourism development and to promote responsible tourism among the stakeholders and tourists. By promoting ecotourism activities and programs in sensitive areas such as rivers or at any water catchment areas can help to promote responsible behavior among the stakeholders and tourists. As a result, this sensitive area will have a longer life span.

While for river awareness and conservation program, the water quality monitoring showed participants have basic knowledge and better understanding about measuring water quality. Since the study area has limited human activity, the water quality at the study site is substantially high. The participants also are more aware about limestone forest ecosystem, particularly their water resources. Not only, were they able to explain eloquently about their experience getting involved in water quality activities during the interview sessions but also this understanding was reflected in their individual reports.

22.5 Study Limitation

Among the limitations faced by this study, it lacked data about limestone forests as a baseline comparison; its hydrological features, geological formation, and vegetation in Malaysia. Also, not many studies are done looking from the social science aspects. Until today, limestone forests and rivers have been studied rarely. Hence, extensive studies relating to this topic should be done in the future for further understanding about water resources and rivers at limestone forest area.

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