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Surpassing Climate Change and Land Degradation

Edited by Surendra N. Kulshreshtha



Sustainable Forest Management - Surpassing Climate Change and Land Degradation

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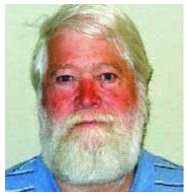
Volume 19

Aims and Scope of the Series

Scientists have long researched to understand the environment and man's place in it. The search for this knowledge grows in importance as rapid increases in population and economic development intensify humans' stresses on ecosystems. Fortunately, rapid increases in multiple scientific areas are advancing our understanding of environmental sciences. Breakthroughs in computing, molecular biology, ecology, and sustainability science are enhancing our ability to utilize environmental sciences to address real-world problems.

The four topics of this book series - Pollution; Environmental Resilience and Management; Ecosystems and Biodiversity; and Water Science - will address important areas of advancement in the environmental sciences. They will represent an excellent initial grouping of published works on these critical topics.

Meet the Series Editor



J. Kevin Summers is a Senior Research Ecologist at the Environmental Protection Agency's (EPA) Gulf Ecosystem Measurement and Modeling Division. He is currently working with colleagues in the Sustainable and Healthy Communities Program to develop an index of community resilience to natural hazards, an index of human well-being that can be linked to changes in the ecosystem, social and economic services, and a community sustainability tool for communities with populations under 40,000. He leads research efforts for indicator and indices development. Dr. Summers is a systems ecologist and began his career at the EPA in 1989 and has worked in various programs and capacities. This includes leading the National Coastal Assessment in collaboration with the Office of Water which culminated in the award-winning National Coastal Condition Report series (four volumes between 2001 and 2012), and which integrates water quality, sediment quality, habitat, and biological data to assess the ecosystem condition of the United States estuaries. He was acting National Program Director for Ecology for the EPA between 2004 and 2006. He has authored approximately 150 peer-reviewed journal articles, book chapters, and reports and has received many awards for technical accomplishments from the EPA and from outside of the agency. Dr. Summers holds a BA in Zoology and Psychology, an MA in Ecology, and Ph.D. in Systems Ecology/Biology.

Meet the Volume Editor



Surendra N. Kulshreshtha is a professor emeritus in the Department of Agricultural and Resource Economics at the University of Saskatchewan, Saskatoon. His areas of research include agroforestry and shelterbelts, irrigation water management, economic impact analysis, greenhouse gas emissions, and climate change. He has edited or coedited 10 books and contributed 91 chapters in books and 178 journal articles. He has been a visiting scientist at the International Institute for Applied Systems Analysis at Laxenburg, Austria, as well as a visiting professor at the Virginia Polytechnique Institute at Blacksburg and the MacDonald College at McGill University. He has served as an editor of the *Canadian Journal of Agricultural Economics* and an associate editor of the *Canadian Water Resources Journal*.

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Preface

Forests cover, according to the World Wildlife Fund, around one-third of all land on Earth and breathe life into our world. But it's not just the planet that suffers when they are destroyed or poorly managed. This is because these natural resources are important for people's lives, homes, and livelihoods and have a crucial role to play in tackling the biodiversity and climate crises. Human health is also closely linked to forest health. Deforestation has serious consequences not only on the pockets of people who are directly dependent on them but also on those living in cities and towns, as it increases the risk of diseases crossing over from animals to humans. Meanwhile, people spending more time in forests (or other similar green areas) has been shown to have a positive benefit on health conditions by the World Wildlife Fund, including cardiovascular disease, respiratory concerns, diabetes, and mental health. According to the UN Environment Program, climate, biodiversity, and land degradation goals will be out of reach unless management and investments into nature-based solutions quickly ramp up. The burning question is how these should be managed.

This book is a novel edited collection of papers dealing with forest management, biodiversity conservation, climate change, and agroforestry. Each of these represents a section in this book through 12 contributions from various parts of the world. These chapters are categorized into four sections.

The first section, "Forest Management", contains two chapters. The first contribution is Chapter 1, written by Keiko Nakayama and Katsuhiro Sakurai, presents the Forest Environment Tax in Japan. This tax was enacted in Japan in 2019 and is due to be levied as a national tax in 2024. The tax would be imposed as a national tax of 1,000 yen (equivalent to U.S. $6.40) per person per year, in addition to the resident tax. The degraded lands connection to sustainable forest management is explored in Chapter 2 by Rajesh Kumar Mishra and Rekha Agarwall. This is a comprehensive review of the literature and includes biodiversity conservation, carbon sequestration, and their socioeconomic benefits. Among the scientific approaches to sustainable forest management, the authors review remote sensing and GIS, forest inventory data, forest health and natural disturbance, landscape ecology, habitat and biodiversity, and adaptive management strategies.

The second section, "Biodiversity Conservation", contains three chapters, although some of the discussion of the biodiversity conservation has already been provided by Mishra and Agarwal in Chapter 2. Chapter 3 is a forest resource value chain analysis, which is suggested by authors as an alternate development pathway for biodiversity conservation. This paper by Mark Aferdi Dadebo, Gordon Kofi Sarfo-Adu, Stephen Omari and David Galley suggests addressing the key concepts of value chain analysis to highlight opportunities. Chapter 4 presents a historical review of environmental conservation in Tanzania. Authored by Hezron Kangalawe, of the University of Dar es Salam, the chapter explores the environmental conservation effort started in 1990, after the Structural Adjustment Program of the World Bank and the International

Monetary Fund, which encouraged sustainable investment in the environment. Chapter 5 is a case study of protected areas in Thailand. The issue of habitat fragmentation in protected areas is addressed by the authors, Krisanadej Jaroensutasinee, Mullica Jaroensutasinee, Orranan Chuachart, Elena Sparrow. They suggest that large protected areas (those larger than 1,600 km^2) are preferred over smaller protected areas to reduce habitat fragmentation.

The third section of the book is devoted to topics related to climate change. In Chapter 6, Emad Yasin, Ahmed A. H. Siddig and Czimber Kornel, based on a study of Sudan, suggest that biodiversity and ecosystems provide crucial services, particularly the indirect benefits such as educational, social, and cultural aspects. They suggest that extreme weather patterns are affecting ecosystems, agriculture, and water resources. Patrush Lepcha, of the Sikkim University, reported results of a review of impact of climate change on mountainous plant species in Chapter 7. This review suggests that climate change can potentially alter, through early spring events and late autumn events, various plant–animal interactions. Climate warming is further removing climatic barriers for invasive plant species. In Chapter 8, Anita Shrestha and Shyam Krishna Shrestha bring a different approach to climate change evaluation by assessing it from a sociological point of view. She suggests that many daily challenges are faced by farmers, particularly those dependent on forest-agriculture and livestock.

The last section of the book contains one chapter. Da B. Tran and Duc Vien Tran, in final Chapter 9, present a summary of agroforestry responses to agricultural expansion in Vietnam. It was reported that after decades of mono agriculture development, farmers in the survey region face a range of problems and consequently began applying agroforestry practices. The authors also suggest that applying multiform cultivation system involving agroforestry and diversity of plants and animals will be a key to sustainable agriculture development in the region.

It is hoped that this volume would serve as a good guide to help the practices of sustainable forest management by present and future forest managers in various parts of the world.

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Section 1

Forest Management

Chapter 1

Japanese Forest Conservation System: The Forest Environment Tax

Keiko Nakayama and Katsuhiro Sakurai

Abstract

Japan is a forest-rich country, with forests covering approximately 70% of its land. It is a well-known fact that forests have a wide range of public functions, including prevention of global warming, conservation of national land, and cultivation of water sources. However, owing to low prices for domestic timber due to cheap imports, a decline in forestry workers, a lack of funds, and an aging population, poorly maintained and degraded forests have become a nationwide problem. Since the 1990s, several local governments have established funds for water resources for forest replenishment as a gesture of gratitude to upstream regions that provide a safe water supply. Furthermore, in 2003, 37 of Japan's 47 prefectures imposed a forest environment tax on prefectural residents, starting with Kochi Prefecture. In 2019, the law of forest environment tax and forest environment transfer tax was enacted, and due to be levied as a national tax in 2024. A unique initiative in the world is a Japanese fund for forest replenishment that began out of gratitude to the upstream regions that provide water. This paper examines the funds and taxes for forest cultivation in Japan, focusing on how they were introduced, accumulated, and collected.

Keywords: forest environment tax, forest environment transfer tax, water source fund, forest conservation, forest management

1. Introduction

The United Nations Strategic Plan for Forests (UNSPF) 2017–2031, which aims to promote the forestry sector's contribution to international goals like the 2030 Agenda, including the sustainable development goals (SDGs), was implemented by the United Nations General Assembly in Ref. [1]. The UNSPF identifies the global forest goals to be attained by 2030 and further targets the details of the goals, which list the specific SDG targets that every global forest goal contributes to.

According to the Global Forest Resources Assessment mentioned in Ref. [2], the global forest area accounts for approximately 4.06 billion hectares (31%) of land area, representing 0.52 hectares per person. The overall rate of net forest loss has significantly decreased between 1990 and 2020 due to the decline in deforestation in several countries and additional afforestation and natural forest growth in other countries. Since then, however, approximately 178 million hectares of forest, approximately five times Japan's area, has been lost due to deforestation.

Japan's forest coverage rate is approximately 70%, which ranks third among the 37 OECD (Organisation for Economic Co-operation and Development) countries after Finland and Sweden, and seventh in the world in planted forest area as given in Ref. [3].

Over the past 50 years, Japan's forested areas have remained unaltered, despite the decline in global forest acreage; thus, encouraging Japan to make the most of its forests could significantly affect the SDGs. Furthermore, planted and natural forests have been increasing annually. Of these, 40% of the total planted forests are fully utilized and older than 50 years, which is the primary cutting period; currently, they are in full-scale utilization. However, the sustainability of using forests is accompanied by the equivalent replacement and growth representing an appropriate maintenance and renewal of trees. Therefore, Japan must prepare sufficient financial resources to contribute to the SDGs. The global warming tax, also known as the "global warming countermeasures tax," was introduced in Japan in 2012; however, it did not incorporate measures to mitigate forest warming. In light of this, imposing a national forest environment tax to raise funds for this endeavor makes sense. Japanese people should pay this tax, whether in the country or abroad.

The structure of this paper is as follows: Section 2 provides the background to introducing funds and taxes for forest cultivation. Section 3 comprehensively describes water source funds from around the country. Section 4 provides an overview of the forest environment tax before developing the national tax. Section 5 presents the forest environment tax as a national tax, which is the focus of this paper. For more information on Section 5, please refer to Ref. [4].

2. Background to establishing the forest environment tax and the water source fund

Forests can enhance people's lives and support national economic growth in many ways. These are considered to be the diverse roles that forests play. The Science Council of Japan contends that forests impact 35 elements in eight categories as given in Ref. [5]. The report aims to quantify the functions; however, the annual monetary estimate of these effects is estimated at 70 trillion yen per annum. Considering that Japan's general account budget for fiscal year 2023 is 114.4 trillion yen, the importance of forest resources is evident.

Following World War II, the Japanese government essentially planned the forestry sector. Massive amounts of hardwoods were felled for munition and rebuilding during and after the war. Additionally, the government implemented an expansion policy of afforestation in cedar and cypress for construction timber. However, the economic liberalization of 1964 enabled timber imports before the trees were old enough for the primary cutting season.

After this long period of stagnation, Japan's forestry industry is finally showing a slightly upward trend. However, the value of forestry output is only one-third of its peak in 1980, the value of standing timber for cypress, cedar, and pine is only approximately one-fourth, and the number of people engaged in forestry and households owning one hectare or more of forest are declining. Due to the long-term slump in the forestry industry, many forests are poorly maintained and fail to meet the functions of the public interest, for example, water source recharge for national land conservation and preventing global warming.

Securing forest absorption capacity is a global trend, and securing financial resources for this purpose was inevitable. Although it is not well known, the government was considering a same-style tax on the water resource fund. Accordingly, the Forestry Agency introduced the "water source tax" in the 1980s. Initially, the rate was 1 yen per 1 m^3 of water used, similar to Toyota City, Aichi Prefecture, which will be described later. Moreover, the Ministry of Land, Infrastructure, Transport and Tourism (formerly known as the Ministry of Construction) introduced a "running water fee." In 1986, these taxes and fees were unified, to enact a bill that would impose a tax of 2.5 yen per 1 m^3 of water used for forest and river maintenance. However, this plan was rejected by the business sector, the Ministry of Finance, Economy, Trade and Industry, and the Ministry of Health, Labour and Welfare. Although the need for forest management was acknowledged, justifying the increased tax burden was difficult because it was unclear who benefited from the public interest function of forests.

Japanese forest ownership was small scale and scattered. Owners' interest in forests decreased due to the long-term stagnation of forestry and changes in ownership over several generations. Hence, forests suffered from mismanagement. For instance, it was common that new trees were not planted after logging. Only 83% of municipalities had many private forests under their control. Other problems included the lack of a land registry, ambiguous property rights, and undefined borders. To achieve the industrialized growth and appropriate management of forests, the "forest management law" was enacted in May 2018, and the corresponding "forest management policy" was established. The forest management system, formally launched in April 2018, aimed to ensure the consolidation and utilization of forests to enhance the growth of the forestry industry and preserve public interest functions through regular maintenance.

Under these circumstances, social interest in the environment has increased, and water source funds have been established in municipalities nationwide. Moreover, the forest replenishment fund was initiated not based on the polluter-pays or the beneficiary-pays principle, but as a gesture of gratitude to the upstream regions that provide water for downstream users. These funds, which have spread throughout Japan, reflect the national character of the Japanese people and are probably unique in the world. Furthermore, the prefecture with the highest forest rate introduced a forest environment tax at the prefectural tax level, and many of Japan's other 47 prefectures followed suit. After 15 years, it was finally decided that a national forest and environmental tax would be established, which would begin to be levied and collected in fiscal 2024, 6 years later.

3. Water source funds

Numerous municipal government organizations have created water source funds since the 1990s. Growing public interest in the environment, particularly the need for a steady supply of pure drinking water, has made this legislation easier. This section will first introduce the tap water source conservation fund of Toyota City, Aichi Prefecture, the first attempt at such a fund in Japan.

3.1 Toyota city tap water source conservation fund

Toyota City, located in the northern part of Aichi Prefecture, is known worldwide as the home of Toyota Motor Corporation. With a total length of 117 km, the

Yahagigawa River is the major river that flows through Toyota City's center and has helped revitalize the area. Since ancient times, this mother river has supported life, has been used in transportation and logistics, and has provided agricultural water to people and industry. Its source is high in the mountains of Nagano Prefecture and flows through Nagano Gifu and Aichi Prefectures. Toyota City is situated in the center of the Yahagigawa River.

Upstream of the Yahagigawa River, forests cover 87% of the area, approximately 60% of which is planted forest. The Yahagigawa River provides Toyota City with over 70% of its raw water needs. In addition, the upstream Yahagigawa Dam supplies water for power generation, agriculture, industry, and pure drinking water.

Nevertheless, the aging population, migration of residents, and drop in timber prices due to imports have all contributed to a major decline in the forestry sector. In the Yahagigawa River basin, afforestation was actively pursued following the war; however, over 50% of the planted forests in the water source basin were neglected, even during periods of thinning. Consequently, rough forests became noticeable throughout the region, despite efforts by forestry officials and local residents to preserve the public interest functions of forests. It is considered desirable that the people who live there, as well as local governments and businesses that benefit from these functions, contribute to these efforts.

Since the early days, the Japanese have worked to protect the water quality and purify the Yahagigawa River basin, believing that "a community with the same basin has the same destiny." The Yahagigawa River water source fund, including 20 towns and villages in the Yahagigawa River basin and Aichi prefecture, was established in 1978. These preconditions enabled the Toyota City tap water source conservation fund to be the first of its kind in the country.

In addition to the city's water charges for upstream forest conservation projects, Toyota City established a tap water source conservation fund in 1993, at a rate of yen per 1 m^2 of used water. The charges of the fund began in 1994. To carry out the project, the city grouped five towns and one village in the upstream area in 2000. Residents perceived the Toyota City Fund as a token of appreciation to the upstream region for providing clean potable water. This project aimed to enhance the water source's replenishment function, which required thinning the planted forests as a main priority.

However, in 2005, the five upstream towns and villages that the fund covered were all merged into Toyota City, and the residents of those towns and villages were also forced to pay for the fund themselves, losing the original meaning of the fund.

This fund was established as an expression of gratitude, not as an obligation to those who live in the downstream areas of the rivers that provide them with pure, potable water, nor as a burden on the beneficiaries. Adopting approach by several local governments has attracted the attention of people nationwide.

3.2 Establishment of multiple water source funds

In 2001, the Ministry of Health, Labour and Welfare and the Forestry Agency surveyed the status of tap water source conservation efforts. The Ministry then conducted a questionnaire survey in 2007 to follow up on water services, investigating distinct initiatives and water utilities involved in conserving potable water sources. Establishing funds, participating in water source forests, forming and organizing watershed councils, aiding upstream wastewater treatment facilities, and establishing ordinances on water source protection were also covered.

There are approximately 35 funds across the country. They are particularly abundant in the Chubu region of Toyota City. The "Gamagori City Tap Water Source Fund" (Aichi Prefecture), "Tap Water Source Environmental Conservation Tax" by the Aichi Chubu Water Supply Corporation[1], the "Misakubo Town Water Source Forest Development Fund" (Shizuoka Prefecture), and "Tap Water Source Environmental Conservation Fund/Kiso Forest Conservation Fund" by the Kiso Wide Area Union[2] have the same purpose and method of accumulation as the Toyota City's fund.

4. Forest environment tax

The country of Japan consists of 47 prefectures. The 47 prefectures are made up of several municipalities called cities, towns, and villages. These municipalities are only differentiated by population and have almost the same functions. If the national government is at the first level, the 47 prefectures are at the second level and the municipalities are at the third level. Thus, Japan has a three-tier administrative system, where each municipality, prefecture, and country can levy taxes independently.

In this section, forest environment taxes levied by the national government are defined as national taxes, those levied by prefectures as prefectural taxes, and those levied by municipalities as city taxes. Note that the fund introduced by many municipalities, such as Toyota City, described in the previous section, is not a tax. However, the purpose of the fund is forest recharge, which is the same as a forest environment tax.

4.1 Prefectural tax

The 1990s saw a growth in the decentralization movement, resulting in financial and administrative reforms, most notably the 1999 "law concerning the development of related laws to promote decentralization." In 2003, Kochi Prefecture became the first region in Japan to impose a tax on forest environments. The decentralization law has allowed local governments to impose taxes independently and significantly streamline the traditional non-statutory ordinary tax. Moreover, low timber prices, a decline in forestry workers, an aging population, and a lack of funding have contributed to the issue of inadequate maintenance of forests that local government bodies manage. The public benefits only from robust forests. Thus, local governments began enacting a forest environment tax using the decentralization law to aid forest restoration.

Kochi Prefecture's forest coverage rate is 74%, ranking first among prefectures in Japan. In addition, Kochi's planted forest per capita is the highest in Japan, approximately six times the nation's average. Thus, 40% of Kochi Prefecture's land was negatively affected, raising concerns about the potential loss of forests' public utility function. In addition, with the lowest financial strength index in the nation, Kochi Prefecture's fiscal situation was tight; therefore, new funding sources were required to prevent the destruction of forests.

Against this backdrop, Kochi Prefecture became the first in the nation to adopt a forest environment tax in 2003. In 2004, Okayama Prefecture imposed the Okayama Forest Building Prefectural Tax, followed by Tottori's Forestry Environmental

[1] The Aichi Chubu Water Supply Corporation is a special local government that supplies water to four cities and one town in Aichi Prefecture.

[2] The Kiso Wide Area Union is made up of six towns and villages in Kiso District, Nagano Prefecture.

Protection Tax, Shimane Prefecture's Tax for Creating Forests with Water and Greenery, Yamaguchi Prefecture's Yamaguchi Forest Creation Prefectural Tax, Ehime Prefecture's forest environment tax, Kumamoto Prefecture's Tax for Creating Forests with Water and Greenery, and Kagoshima Prefecture's forest environment tax in 2005. **Figure 1** shows that of Japan's 47 prefectures, 37 have adopted a forest environment tax under different names.

A forest environment tax can be defined as a system where local governments enforce an additional tax burden to conserve or recharge forests. However, no tax falls under the forest environment tax category. The introduced forest environment tax used the per capita approach that provides the necessary funds to safeguard forests through a taxation surcharge on inhabitants (prefectural or municipal taxes) mandated by the local tax law. Accordingly, the residence tax is a regular tax collected without a stated goal. Forest conservation initiatives are financed with funds equal to the tax surcharge collected as a forest environment tax.

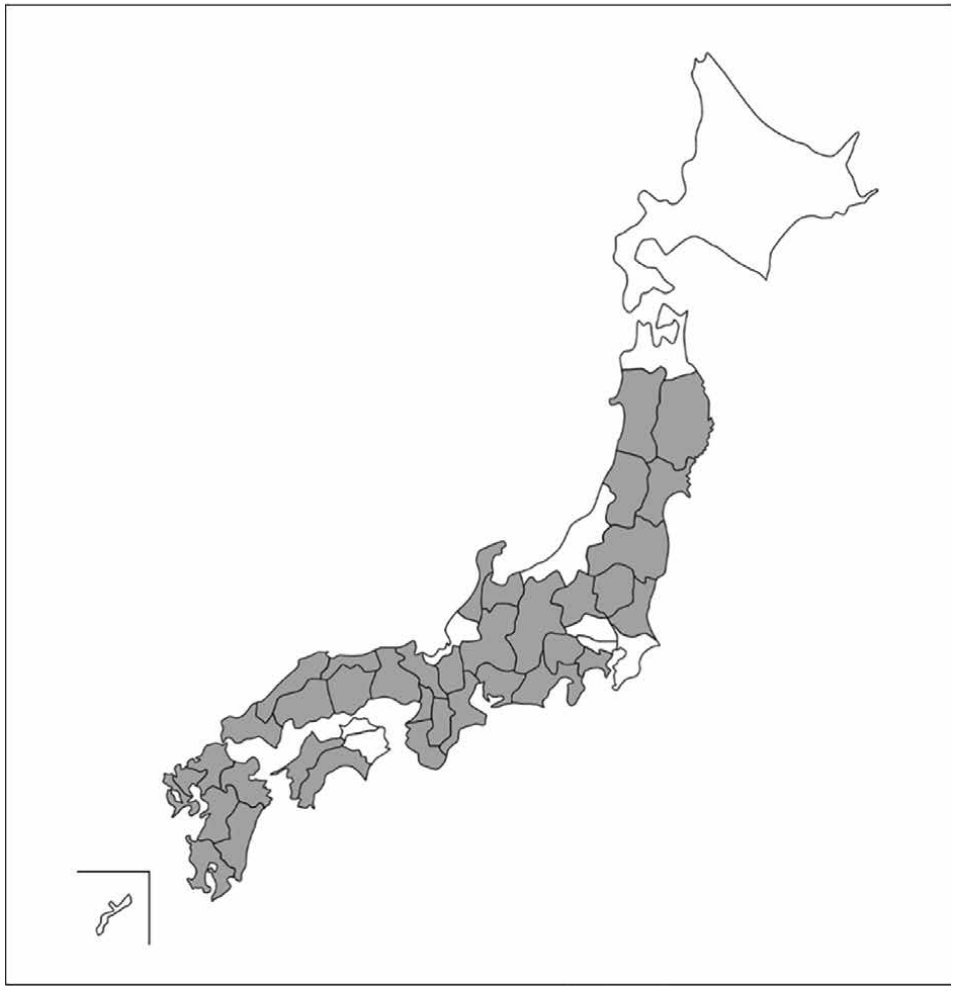


Figure 1.
Prefectures that have introduced substantial forest environment tax (shaded area). Created by the authors based on Ref. [6].

Most prefectures impose an excess tax of forest environment tax at a fixed rate per capita on corporations, where the amount is determined according to specific criteria such as capital, and a flat excess tax rate on individuals' per capita residential tax rate. Kochi Prefecture, in contrast, levied a flat tax surcharge on the per capita rates of individuals and corporations. The annual burden per individual in most prefectures is 500–1,000 yen. The Kochi Prefecture charges the minimum rate.

Prefecture-introduced forest environment taxes have specific characteristics: Since 2003, every local government has rapidly moved toward making such taxes law. Second, the method of tax collection necessitates a fair and moderate tax burden for all prefecture residents. Notwithstanding some variances, the tax is only as high as what residents can bear. Third, most local governments work toward reforestation using thinning where appropriate for the surrounding environment and local areas. However, there are variations in the other projects that have been chosen.

The forest environment tax differs slightly from other environmental taxes because it is local. It is not an incentive scheme in which a polluter assumes the environmental burden by paying the costs of the amount of damage inflicted. Nor does the beneficiary burden principle apply, in which the policy's beneficiaries must pay the bill. In what is known as the joint burden or the participation principle, the current forest environment tax requires residents to share the cost of a certain amount of tax surcharge.

4.2 City tax

Yokohama City, located in Kanagawa Prefecture, has a unique city tax: the "Yokohama Green Tax," which, introduced in 2009, promotes the "Yokohama Green-Up Plan" to green the city and ensure its sustainability continues to the next generation. Individuals will be charged 900 yen per year, and corporations will be charged an additional amount equivalent to 9% of the annual per capita corporate municipal tax.

Considering the forest environment tax, not the forest and forestry fields, many discussions exist in environmental economics, law, finance, and other areas. Despite this, the results from the resident questionnaire survey indicate that the prefecture's forest environment tax is generally considered positive.

4.3 National tax

The government has been working and collaborating with pertinent stakeholders for several years to secure funding to preserve and enhance public interest activities. In this context, the Kyoto Protocol was approved at the third session of the 1997 Conference of the Parties (COP3) and was enacted in 2005. At the 17th session of the Conference of the Parties (COP17) held in 2011, a path toward a future framework was also agreed upon. This implies that to meet its greenhouse gas emission reduction target, Japan must protect its forests and acquire funding for initiatives such as thinning. The Ministry of Agriculture, Forestry and Fisheries has requested a tax to fund forest sink initiatives since 2004.

Nevertheless, every region also appealed to the national government to provide funding. Since 2006, local council members have advocated for a forest environment tax through the National Federation of Parliamentarians for the Promotion of Forest Environment Tax Creation and the National Federation for Promotion of Forest Environment Tax Creation, founded by municipalities with extensive forests. The

Kochi Prefecture led 34 organizations in implementing the forest environment tax by 2014. This local tax aimed to raise funds for an additional inhabitant tax for forests. Furthermore, a new international framework to address global warming was adopted in 2015 with the Paris Agreement. Then, with public support for forest preservation growing, the 2018 Tax Reform Charter finalized the implementation of the forest environment tax. The Tax Reform Charter stated that the Ministry of Agriculture, Forestry and Fisheries considered building a forest management system and that the forest environment tax will be imposed in the fiscal year 2024, while the forest environment transfer tax began in fiscal year 2019. Additionally, it requested that funding be allocated to cover forest thinning, securing leaders, human resource development, and maintenance of forests, encouraging the use and distribution of wood, public education for municipalities and prefectures, and promotion costs, with prefectures supporting municipalities that maintain their forests. The Cabinet approved the general guidelines for tax reform in 2018, and in 2019, the forest environment and forest environment transfer taxes were passed. It was partially implemented in April of that year.

Commencing in 2024, municipalities will impose a national tax of 1,000 yen per year for the forest environment, which will be based on the individual inhabitant tax per capita rate. Additionally, the forest environment transfer tax, financed by the allocation tax and borrowings in the forest management system, was introduced in response to the pressing need for forest maintenance. Transfers began in September and March of the fiscal year 2019. Municipalities and prefectures are assumed to receive a proportionate share of these funds, with 20% going to forestry workers, 30% to the population, and 50% to privately owned forests. However, municipalities must declare the purpose of the forest environment transfer tax to ensure the tax is applied appropriately (refer to Refs. [7, 8]). **Figure 2** shows an overview of the forest environment tax and forest environment transfer tax described in this section.

Stakeholders oppose treating the forest environment tax as a national tax. One reason is the overlap between the prefectural and forest environment taxes. In the future, it will be necessary to clearly differentiate the use of national and prefectural taxes.

The rationale of the tax is the next thing to think about. Numerous studies contest the tax's foundation. Even though the forest is also used for greenhouse gas absorption, it makes sense that the beneficiary will pay a fee if the objective is to secure the forest's water source to guarantee a drinkable water supply. Many people are calling for businesses that emit emissions to be subject to "polluter pays" taxes. Furthermore, it has been pointed out that the policy effects aimed at tax increases are highly unclear.

There is a massive criticism of excessive taxation. A frequent concern is that there will be double taxation in 37 prefectures. Yokohama City and Kanagawa Prefecture are the sources of the Yokohama green tax and the water source environment tax; therefore, residents of Yokohama are subjected to triple taxation. A similar phenomenon occurs in areas where prefectural forest environment taxes and funds have been introduced, like Toyota City. The forest environment tax employs a taxation surcharge method for the inhabitant tax, which reduces resistance and is more straightforward for locals to understand than other taxes. However, it is questionable if a tax this simple to administer is fair and equitable.

Finally, we discuss the transfer standard for the forest environment transfer tax. In fiscal year 2019, the first year, approximately 20 billion yen were allocated to prefectures, approximately 4 billion yen, and to municipalities, approximately 16 billion yen. However, when looking at the amount allocated to Yokohama City, Kanagawa

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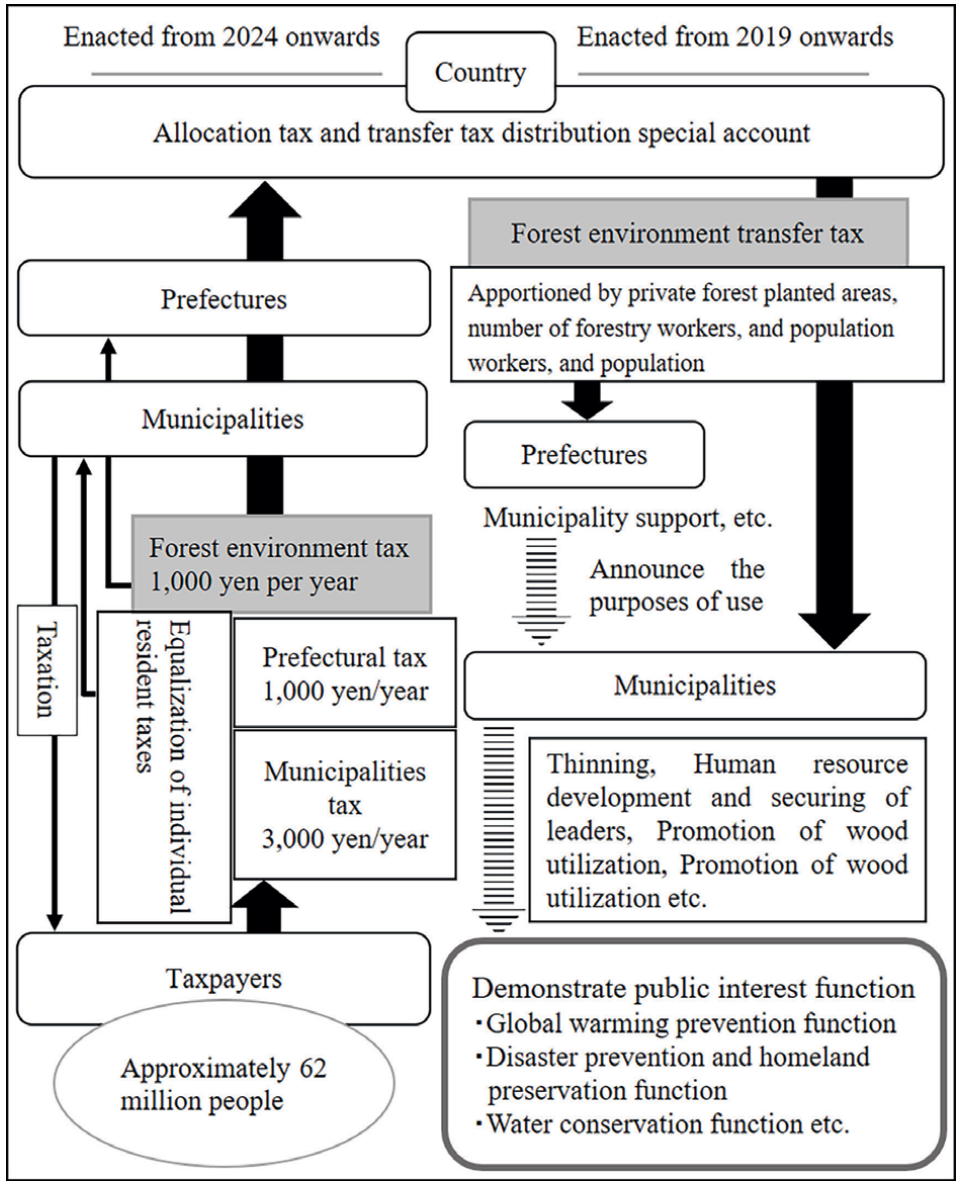


Figure 2.
Mechanism of forest environment tax and forest environment transfer tax. Created by the authors based on Ref. [9].

Prefecture ranked first, followed by Hamamatsu City, Shizuoka Prefecture, and Osaka City, Osaka Prefecture. Seven ordinance-designated cities were included in the top 10 local governments. Since the population accounts for 30% of the concession criteria, the amount granted to Kurihara City, which has an area of approximately 10,000 hectares of privately owned artificial forests, is the same as the amounts granted to Osaka City, Setagaya Ward, Tokyo, and Nerima Ward, Tokyo, which have no privately owned forests. The amount was less than the amount granted. This phenomenon has occurred across the country where large amounts of land are given to urban areas, while less is given to areas with large forest areas.

There are 792 cities in Japan (as of October 1, 2022), but designated cities must have the same administrative and financial capabilities as prefectures, so they currently have a population of approximately 70. Twenty cities with a population of over 10,000 people have been designated by government ordinance, and their population accounts for approximately 20% of the total population. Total tax payments are scheduled to increase yearly, exacerbating people's dissatisfaction in forested and depopulated areas.

According to a government report, approximately 84 billion yen have been allocated to municipalities nationwide in the 3 years since the system began in 2019. However, 47% of that amount, or 39.5 billion yen, is not being utilized. In August 2023, the Forestry Agency announced that the forest environment transfer tax accounted for 40 billion yen in fiscal 2022 (municipal portion: 34.1 billion yen, prefecture portion: 5.8 billion yen), and the utilization rate of the transfer amount is 80%. Nearly 50% of the forest environment transfer tax was used, and 20% remains unused in fiscal year 2022 because the amount is destined for urban areas with large populations under the current allocation standards. Therefore, in the 2024 tax reform, the government is adjusting the distribution standards to allocate more to local governments with large forest areas.

5. Concluding remarks

Forest recharge is essential to contribute to the SDGs and requires sufficient financial resources. In Japan, Toyota City was the first to establish a fund for forest recharge in 1993, and this municipal-level initiative has expanded nationwide. In 2003, Kochi Prefecture introduced a forest environment tax at the prefectural level. Currently, 37 of the 47 prefectures have also introduced it. From 2024 onwards, a forest environment tax will also be levied as a national tax. The system of collecting funds for recharging forests at each administrative level is unique to Japan as a forest-rich country.

From fiscal 2024, a "forest environment tax" will be collected as a national tax of 1,000 yen per person from those living in Japan, in addition to the resident tax. If there are approximately 62 million taxpayers, tax revenue is expected to reach 62 billion yen per year. The tax revenue will be distributed to all prefectures, towns, and villages nationwide as a "forest environment transfer tax." Although problematic factors have been identified in the forest environment tax, there is no doubt that it will contribute to maintaining the forests' public functions as a financial resource for forest recharge, along with the forest environment tax as a prefectural tax and water resource recharge throughout the country. In the future, I hope that Japan's unique forest environment tax will become a model for forest cultivation worldwide, as it continues to make improvements, including reviewing the concession criteria and resolving issues.

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Chapter 2

Sustainable Forest Land Management to Restore Degraded Lands

Rajesh Kumar Mishra and Rekha Agarwal

Abstract

Deforestation and degradation of the global forests have led to the degradation of the environment, the economy, and the esthetics of the forestlands. Deforestation and degradation have been compensated to some degree by the natural regeneration of the forests and the setting up of plantations, but much-regenerated forest is composed of a small number of species designed to produce one or two types of products rather than to produce a wider variety of forest products and services that contribute to the prosperity of the local community. Conventional models of plantation forestry rarely provide the multiple values of forests and do not adequately address the needs of the forest-dependent communities and the water users downstream. In reality, such systems can lead to a decrease in the variety, quality, and volume of forest products and services, as well as social and economic displacement and an increase in vulnerability to climate and other natural shocks. There is a pressing need to both enhance the quality of the restoration and rehabilitation of the forest at site level, as well as to identify effective ways to carry out these activities within the context of wider environmental, social, or economic interests. While forest land use has traditionally been seen as a local environmental challenge, it is now becoming a global challenge. Changes to forests, farms, waterways, and air are driving global changes to the food supply, fiber supply, water supply, shelter supply, and air supply for more than 6 billion people. In recent decades, global cropland, pasture, plantation, and city areas have grown in size and increased energy, water, and fertilizer use, with significant biodiversity loss. These land-use changes have allowed humans to appropriate more and more of the planet's resources. But they also threaten the ability of ecosystems to support food production, freshwater and forest supply, climate and air regulation, and disease control. We are confronted with the challenge of balancing immediate human needs with maintaining the biosphere's capacity to deliver goods and services over the long term. As our population continues to grow and our demand for land and resources increases, so too does the pressure on forest ecosystems. Many forests that remain are decimated by logging, cutting firewood, pollution, and pests. Even trees that are left are disappearing to make room for houses, roads, dams, and intensive agriculture. Climate change-driven wildfires can also wreak havoc on forest ecosystems. Forest restoration is the process of returning trees to previously forested land and improving the state of degraded forests. It involves planting native tree species to restore the tree cover in existing forests. It also includes the conservation of wild plants and animals, as well as preserving the soils and

water resources that are part of a forest ecosystem. Land that has been cleared for farming but is now being used for other purposes is a great place to restore forests. In some instances, forest trees will naturally re-grow. Restoration can also include the nurturing of forest and woodland patches in landscapes that include busy farms and settlements.

Keywords: sustainable land management, land degradation, climate change, livelihood, ecosystem services

1. Introduction

Around the world, there is a growing demand for products and services derived from limited forest land resources. For example, the amount of forest land available to feed a person in 1961 dropped from 0.45 to 0.20 ha in 2005. Factors such as climate change, population, globalization, and inadequate land management practices have led to a loss of supply and ecosystem services (i.e., carbon sequestration and nutrient cycling) maintained by land. Some degradation is natural, such as those caused by earthquakes and landslides, while the majority of degradation is human-induced, including deforestation, overgrazing, urban sprawl, etc. Degradation also leads to a loss of forest cover, biodiversity, and vegetation, which in turn contributes to climate change. According to the UN Food and Agriculture Organization (FAO), one in every three people on earth is affected by land degradation at some point in their lives. A recent study estimates the annual global costs of land degradation at around $300 billion US dollars. The global community has responded with the aim of achieving a state of 'Land Degradation Neutrality' in addition to fulfilling other ambitious commitments in terms of climate and biodiversity.

Sustainable land management can help make these commitments a reality. Sustainable forest land management is a collection of practices, technology, and methodologies designed to maintain indefinite ecological integrity and stability of ecosystem services while ensuring sustenance and diversity of livelihoods for humans. By rehabilitating degraded forest land through ecosystem rehabilitation and sustainable neighborhood design, Sustainable forest land management can protect critical ecosystems and support businesses. Sustainable forest land management can help reverse the current rate of degradation. However, large-scale sustainable forest management (SFM) interventions must be evaluated on the basis of their overall value (environmental, social, and economic).

Millions of hectares of forests around the world have been destroyed or are in danger of being destroyed, and landscapes all over the world are becoming easier to manage through land-use trends. In many tropical countries, increasing amounts of forest or woodland have been cleared for agriculture. The same can be said for some temperate countries, although land-use patterns in these countries have largely stabilized over the past century. However, agricultural practices are increasing in many temperate countries. In many tropical and temperate countries, small family-owned farms have been replaced by large industrial farms owned by corporations. Forest remains and hedgerows have been removed to allow for large-scale operations. As a result, tropical and temperate forest lands are becoming homogenized. In addition, there is an increasing amount of abandoned land. In some cases, previous forms of agriculture have been unsustainable, and farmland has been abandoned as productivity has declined. In others, such as in Western Europe, socioeconomic changes have led to the abandonment of productive agricultural land. As a result of agricultural

expansion and intensification, the total area of forest and woodland has decreased, the structure of remaining forests has been simplified, and forest areas have been fragmented into smaller and isolated fragments.

2. Sustainable forest land management

Forest land management is an integral part of environmental protection and plays an important role in preserving ecological equilibrium, biodiversity, and ecosystem health. Sustainable forest land management combines ecological, social, and economic considerations to ensure forests are managed in a way that meets current needs while allowing future generations to fulfill their own needs.

2.1 Importance of sustainable forest land management

Sustainable forest land management is crucial for several reasons:

2.1.1 Biodiversity conservation

Biodiversity conservation is a critical aspect of sustainable forest land management, and it involves the protection and sustainable use of the rich variety of life within forest ecosystems. This encompasses not only diverse species of plants and animals but also the intricate interactions and ecological processes that contribute to the overall health and resilience of the forest. Here, we delve into the scientific foundations, challenges, and innovative approaches related to biodiversity conservation in the context of forest land management. Forests harbor a vast array of plant and animal species. Sustainable management practices aim to maintain and enhance biodiversity by preserving habitats, preventing deforestation, and promoting sustainable harvesting techniques [1].

Biodiversity is essential for pollination, purification of water, nutrient cycling, and other ecosystem services that are essential for human health [2]. Scientific studies emphasize the interconnectedness of species and their contribution to maintaining ecological balance [3]. The concept of keystone species and trophic cascades is essential in biodiversity conservation. Keystone species exert a disproportionate influence on ecosystem structure, and disruptions to their populations can trigger cascading effects throughout the food web [4]. Invasive species and climate change are two of the biggest threats to biodiversity. Scientific research helps predict and understand the potential effects of these factors on forest ecosystems [5].

As human populations expand and interact with forest ecosystems, conflicts with wildlife can arise. Scientific approaches focus on understanding and mitigating these conflicts to ensure coexistence between humans and biodiversity [6]. Advancements in genomics provide valuable insights into the genetic diversity of populations, enabling more targeted conservation efforts. This includes the use of techniques such as DNA bar-coding and genomics to assess and monitor biodiversity [7]. Incorporating citizen science initiatives and leveraging technology, such as smart phone apps and remote sensing, enhances the monitoring and conservation of biodiversity. This inclusive approach fosters public engagement and data collection [8]. Biodiversity conservation in sustainable forest land management is a dynamic and interdisciplinary field that requires continuous scientific inquiry. By integrating ecological principles, cutting-edge technologies, and community involvement, we can strive to safeguard the incredible diversity of life within forest ecosystems.

2.1.2 Carbon sequestration and climate change mitigation

Carbon sequestration in forest ecosystems is a crucial component of sustainable forest land management, contributing significantly to global climate change mitigation efforts. The process involves capturing and storing atmospheric carbon dioxide (CO2) in vegetation, soils, and woody biomass, thereby helping to offset the impacts of anthropogenic greenhouse gas emissions. In this discourse, we shall delve into the scientific principles, methodologies, and hurdles linked to the process of carbon sequestration in forests, with a particular focus on its significance in combating climate change. Forests serve as crucial repositories for carbon, actively absorbing and retaining substantial quantities of carbon dioxide. Sustainable forest management helps combat climate change by preventing deforestation, promoting afforestation, and implementing carbon-friendly logging practices [9].

Forests act as substantial carbon sinks by absorbing CO2 during photosynthesis. Trees store carbon in their biomass, including leaves, stems, and roots. Additionally, soil organic matter in forest ecosystems holds a considerable amount of carbon [10]. Scientific studies delve into the complex dynamics of carbon cycling in forests, examining factors such as tree growth, decomposition, and the influence of disturbances on carbon storage. Understanding these processes is crucial for effective management strategies [11].

Accurate measurement of carbon sequestration involves comprehensive forest inventories and continuous monitoring. Scientifically established protocols, including field measurements and remote sensing technologies, contribute to assessing changes in forest carbon stocks over time [12]. Remote sensing, coupled with Light Detection and Ranging (LiDAR) technologies, provides valuable insights into forest structure and biomass. These tools enable large-scale assessments of carbon stocks and changes in forest cover [13]. Deforestation remains a significant challenge to carbon sequestration efforts. Scientific research focuses on understanding the drivers of deforestation and implementing strategies to reduce land-use change, such as sustainable logging practices and reforestation initiatives [14]. Climate change itself poses risks to forests, affecting their ability to sequester carbon. Scientific investigations explore the potential impacts of changing climatic conditions on forest ecosystems and develop adaptive strategies [15].

Global efforts such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) strive to offer economic incentives to nations, encouraging them to conserve and manage their forests in a sustainable manner. Scientific assessments contribute to the development and evaluation of these policies [16]. Collaborative research efforts, facilitated by international organizations and scientific networks, play a pivotal role in advancing our understanding of carbon sequestration. Shared knowledge contributes to the development of best practices for climate change mitigation [17]. Carbon sequestration in forests is a scientifically grounded strategy for mitigating climate change. Sustainable forest land management, informed by ongoing research, is essential for maximizing the carbon sequestration potential of forests.

Approximately 861 gigatonnes of carbon are stored in the world's forests, distributed as follows: 44 percent in soil (up to a depth of 1 meter), 42 percent in live biomass (both above and below ground), 8 percent in dead wood, and 5 percent in litter [10, 18]. Collectively, this amount is nearly comparable to the fossil fuel emissions generated annually over almost a century. Despite tropical rainforests covering only 30 percent of the global tree canopy, they harbor 50 percent of the carbon stored in trees worldwide [19]. Tropical forests store most of their carbon in vegetation (biomass), and boreal forests store vast amounts of carbon in soils [20].

2.1.3 Socioeconomic benefits

Socioeconomic benefits derived from sustainable forest land management are multifaceted, encompassing contributions to local communities, regional economies, and global well-being. The integration of social and economic considerations in forest management is essential for achieving long-term sustainability. In this discourse, we will investigate the scientific underpinnings and empirical observations regarding the socioeconomic advantages linked to the sustainable management of forest lands. Sustainable forest management enhances the welfare of local communities by furnishing livelihood opportunities, preserving traditional practices, and guaranteeing a consistent provision of forest resources. This approach balances the economic benefits derived from forests with the need for long-term ecological resilience [21]. Scientific studies demonstrate that sustainable forest management creates employment opportunities, particularly in activities such as timber harvesting, non-timber forest product collection, and ecotourism. These activities contribute to local economies and provide a source of income for communities [22].

Studies underscore the significance of sustainably harvesting both timber and non-timber forest products, stressing the need to control extraction rates to preserve ecosystem health while fulfilling economic requirements [23]. Scientifically informed approaches recognize the value of indigenous and local knowledge in sustainable forest management. Research demonstrates that incorporating traditional practices can enhance the effectiveness of conservation efforts and promote community engagement [24]. Research underscores the effectiveness of collaborative forest management frameworks, wherein local communities are actively engaged in decision-making processes. This approach nurtures a sense of ownership, resulting in enhanced conservation results and better socioeconomic circumstances [25]. Sustainable forest land management contributes to global climate regulation by enhancing carbon sequestration and mitigating climate change. Scientific assessments quantify the role of forests in sequestering carbon and the implications for global climate patterns [26].

Forests are indispensable in the management of water resources, as they actively regulate the flow of water, mitigate soil erosion, and uphold water quality. Scientific evidence supports the importance of forests in providing these ecosystem services, benefiting both local communities and downstream users [27]. Scientific research identifies the challenges posed by illegal logging and unsustainable forest practices. Understanding the socioeconomic drivers of these activities is crucial for developing effective strategies to combat them [28]. Studies assess the effectiveness of forest certification schemes and market-based mechanisms in promoting sustainable practices. Scientific evaluation informs ongoing efforts to improve the credibility and impact of these initiatives [29]. Sustainable forest land management, grounded in scientific research, offers a balance between ecological conservation and socioeconomic benefits. Ongoing studies contribute to refining management practices, ensuring that forests continue to provide essential services for local communities and the global environment. Your insights or questions on specific aspects of the socioeconomic benefits of sustainable forest land management are welcome.

2.2 Scientific approaches in sustainable forest land management

2.2.1 Remote sensing and geographic information system (GIS)

Remote Sensing (RS) and Geographic Information System (GIS) technologies are instrumental in facilitating sustainable forest land management through the provision

of essential tools for monitoring, analysis, and decision-making processes. These advanced technologies offer a comprehensive and spatially explicit understanding of forest ecosystems, aiding in the development and implementation of effective management strategies. Let us explore the scientific foundations, applications, and future prospects of Remote Sensing and GIS in the context of sustainable forest land management. Cutting-edge technologies like satellite imagery and Geographic Information Systems (GIS) are pivotal in monitoring forest dynamics, evaluating alterations in land use, and pinpointing areas that are susceptible to risks. These tools enable precise data-driven decision-making in sustainable forest management [30].

Remote Sensing relies on satellite imagery that captures data across different spectral bands. Scientific analysis of these spectral signatures enables the identification of land cover types, forest health, and changes over time [31]. Light Detection and Ranging (LiDAR) technology, often used in conjunction with RS, provides high-resolution three-dimensional mapping of forest structures. Scientific applications include measuring canopy height, biomass estimation, and identifying topographic features [32]. Remote Sensing and GIS facilitate accurate and cost-effective forest inventory and monitoring. Scientifically validated methods include the use of satellite imagery and LiDAR data for estimating forest biomass, species composition, and changes in land cover [33]. Scientific applications of RS and GIS enable the detection of deforestation and changes in land use. Continuous monitoring assists in identifying areas at risk and assessing the impacts of human activities on forest ecosystems [34]. The increasing volume of remote sensing data poses challenges for data storage and processing. Scientific advancements in cloud computing and big data analytics facilitate the efficient handling and analysis of large datasets, enhancing the scalability of RS and GIS applications [35].

Scientific approaches involve integrating data from various sources, including satellite imagery, ground-based sensors, and social data. This multi-source integration enhances the accuracy and reliability of forest assessments [36]. Scientific exploration of machine learning and artificial intelligence in RS and GIS holds promise for automating image interpretation, classification, and feature extraction. These technologies contribute to more efficient and accurate forest monitoring [37]. Advancements in hyperspectral imaging enable the acquisition of detailed spectral information. Scientific research focuses on utilizing hyperspectral data for enhanced ecological insights, such as species identification and stress detection [38]. Remote sensing and GIS, guided by scientific principles, are invaluable tools in sustainable forest land management. Ongoing research and technological innovations continue to refine these methodologies, contributing to a more comprehensive understanding of forest ecosystems and supporting evidence-based decision-making.

Forest managers have experienced a steady rise in the adoption of remote sensing, largely driven by improved integration of imagery with GIS technology and databases, along with tailored implementations that meet the specific information requirements of forest management [39].

2.2.1.1 Forest inventory data

Stand boundaries are a vector-based representation of homogeneous forest characteristics. Forest inventory databases are primarily based on manual interpretation of stand boundaries from aerial photographs. Stand polygons are characterized by a collection of attributes that typically include species composition, stand height, stand age, and crown closure. Digital remotely sensed data can also be used to update inventory databases with change (e.g., harvest) data for quality control and audit and to detect

bias. It can be used to add additional attribute information and detect biases in forest inventory databases based on vintage, map sheet boundary, or interpreter preferences.

Managing forests sustainably for a variety of timber and non-timber values has necessitated the collection of more granular tree and stand data as well as additional information such as gaps and distribution. Within-stand forest inventory data can be derived from high-resolution remote sensing, including large-scale aerial photographs and airborne digital imagery (ADI). There are two ways to obtain this information: polygon decomposition (PCD) [40] or individual tree crown recognition (ICR) [41].

Polygonal decomposition looks at the number of pixels representing the forest polygon in a remote sensing image and generates new data that is added to your forest inventory database [40]. For instance, change detection analysis on multi-pixels satellite images from the Landsat Thematic Mapper can tell you the area and the percentage of pixels where the environment has changed. Individual tree crown recognition looks at high-resolution images, which can be used to derive tree crown characteristics (crown area, stand density, and volume) [41].

2.2.1.2 Forest health and natural disturbances

Forest management planning and monitoring objectives rely on accurate inventory databases, which must be regularly updated to account for significant natural disturbances such as fire, insects, and disease. Keeping these databases current is crucial for effective forest management.

2.2.1.2.1 Insect disturbance

Defoliators and bark beetles rank among the most destructive insects to trees [42]. Assessing the damage caused by these insects usually involves a two-step procedure: first, mapping the affected area and then quantitatively evaluating the extent of tree damage within the mapped regions.

The predominant method for mapping areas damaged by insects has been aerial sketch-mapping, where human observers manually annotate maps or aerial photographs [43]. While this approach is commonly utilized, it is associated with high costs, subjectivity, and spatial imprecision. Nonetheless, by complementing it with ground survey techniques and integrating remote sensing and GIS analysis, significant advantages can be attained.

2.2.1.2.2 Forest fire

Fire is an ecological mechanism dictating the composition, distribution, and succession patterns of vegetation within the landscape [44]. Understanding fire disturbance is essential for the following purposes:

- Assessing the impact of fire on both timber and non-timber values.
- Identifying opportunities for salvage logging.
- Examining the influence of climate change and associated feedback mechanisms on forest fire frequency.
- Quantifying the impact of fire on carbon budgets at regional, national, and global scales [45].

To tackle this array of challenges, foresters utilize a variety of fieldwork techniques, alongside global positioning system (GPS) technology, as well as remote sensing methods and data from both airborne and satellite platforms.

Integrated fire support systems combining remote sensing and GIS are utilized for real-time, near-real-time, and post-fire applications.

For instance, infrared and thermal-infrared cameras equipped with integrated GPS/INS (inertial navigation system) technologies can detect fire hotspots, active fires, and fire perimeters in real-time. Information regarding the fire's location and extent is transmitted from the aircraft to ground-based systems, enabling precise guidance to be provided to water-bombers and firefighting teams.

2.2.1.3 Landscape ecology, habitat, and biodiversity

To ensure sustainable forest land management, forest inventory, and certification procedures must incorporate landscape ecological features relevant to habitat and biodiversity [46]. These features encompass spatial patterns within the landscape, specific forest conditions related to habitat, and the ecological processes that connect spatial patterns, habitat, and ecosystem functioning.

One instance of spatial patterns readily accessible is land-cover data, obtained by classifying remotely sensed information. Additionally, valuable datasets encompass forest canopy details (such as crown closure or estimates of leaf area), understory information [47], and metrics delineating the distribution and boundaries of landscape units like forest fragmentation [48]. Remote sensing offers reliable and consistent techniques for generating these data layers, enabling the monitoring of temporal changes and the development and validation of habitat models tailored to individual species.

Emerging radar applications are under development to penetrate the forest canopy, unveiling insights into the characteristics of the forest floor. Innovations like LiDAR offer estimations of forest biomass, height, and the vertical distribution of forest structure with unparalleled precision [47]. Leveraging advanced digital analysis techniques and judicious integration of complementary data sources have yielded unprecedented levels of detail regarding forest structure, function, and ecosystem dynamics [41, 49].

2.2.2 Adaptive management strategies

Adaptive management represents a scientific methodology for sustainable forest land management, wherein lessons are gleaned from the consequences of management interventions, and strategies are modified in response to continual monitoring and research findings. This dynamic and iterative process allows for flexibility in responding to uncertainties, changing environmental conditions, and evolving knowledge. Scientifically informed adaptive management involves continually assessing the effectiveness of management strategies and adjusting them based on ongoing monitoring and research. This approach allows for flexibility in responding to uncertainties and changing conditions [50]. Adaptive management is rooted in the principles of systematic learning and experimentation. Scientific studies emphasize the importance of treating management activities as experiments, where outcomes are carefully observed and analyzed to inform future decisions [51].

Scientific frameworks for adaptive management stress the need for feedback loops and iterative processes. Monitoring and assessment provide critical feedback, allowing managers to continuously adjust their strategies based on new information

[52]. Scientifically guided adaptive management begins with clear and measurable objectives. Hypotheses about the potential outcomes of management actions are developed, providing a basis for structured experimentation [50]. Adaptive management relies on rigorous monitoring and evaluation processes. Scientifically robust data collection allows for the assessment of whether management objectives are being met and helps identify unexpected outcomes [53]. In fire-prone ecosystems, adaptive management involves experimenting with controlled burns and monitoring their ecological effects. Scientific studies help refine fire management strategies, considering factors like species composition, biodiversity, and soil health [54].

Adaptive management in timber harvesting involves experimenting with different harvesting techniques and rotation lengths. Scientific assessments inform decisions about sustainable harvest levels, regeneration methods, and the impact on biodiversity [55]. Scientific literature highlights the challenges posed by institutional barriers to adaptive management. Overcoming these barriers requires collaborative efforts, stakeholder engagement, and a willingness to adapt policies and regulations [50]. Effective communication and knowledge transfer are essential for successful adaptive management. Scientifically informed approaches emphasize the importance of sharing lessons learned, best practices, and research findings among stakeholders [56].

Advancements in modeling and simulation techniques offer opportunities for refining adaptive management strategies. Scientific models help predict potential outcomes, test scenarios and assess the robustness of different management approaches [57]. Scientific research advocates for an integrated social-ecological systems perspective in adaptive management. This involves considering the interconnectedness of social and ecological factors and understanding how they influence each other [58]. Adaptive management, grounded in scientific principles, is a powerful approach to navigating the complexities of sustainable forest land management. Continuous learning, experimentation, and the incorporation of new knowledge ensure that management strategies remain effective and resilient in the face of environmental uncertainties.

3. Conservation strategies in sustainable forest land management

3.1 Protected areas and reserves

Protected areas and reserves are fundamental components of sustainable forest land management, serving as crucial tools for biodiversity conservation, ecosystem protection, and sustainable resource use. Scientifically guided establishment, management, and assessment of these areas are essential for ensuring their effectiveness in preserving biodiversity and maintaining ecosystem services. Establishing protected areas and reserves is a fundamental strategy for conserving biodiversity. Scientific assessments help identify areas of high ecological value, ensuring that these zones serve as refuges for diverse flora and fauna [59]. The establishment of protected areas is grounded in conservation biology principles, emphasizing the need to maintain representative samples of diverse ecosystems to conserve biodiversity. Scientific studies contribute to the identification of priority areas and the understanding of ecological processes [60]. Scientific insights from landscape ecology contribute to the design and connectivity of protected areas. Understanding landscape patterns, habitat corridors, and species movements helps ensure the ecological viability of protected landscapes [61].

The scientifically informed design of protected areas follows the principles of representation, replication, and redundancy. This involves ensuring that protected areas

represent the diversity of ecosystems, are replicated across landscapes, and provide redundancy for species and ecological processes [62]. Protected areas benefit from adaptive management strategies, allowing for flexibility in response to changing ecological conditions. Scientifically grounded adaptive management incorporates ongoing monitoring, assessment, and adjustment of management practices [63]. Scientific research contributes to the establishment and management of national parks and wilderness areas. These areas aim to protect pristine ecosystems, maintain biodiversity, and provide opportunities for scientific research and environmental education [64].

Scientifically guided community-based conservation involves local communities in the management of protected areas. This approach recognizes the importance of traditional ecological knowledge and local stewardship in achieving conservation goals [65]. Scientific studies address challenges related to human-wildlife conflict in and around protected areas. Understanding the drivers of conflicts and implementing mitigation strategies contribute to sustainable coexistence [66]. Protected areas face challenges related to climate change impacts. Scientific research explores adaptation strategies, such as assisted migration and habitat restoration, to help species cope with changing conditions [67]. Advancements in landscape genetics and connectivity modeling offer opportunities for optimizing protected area design. Scientific research contributes to identifying key corridors and improving landscape connectivity for wildlife [68].

A significant global concern revolves around the potential depletion of fisheries, forests, and water resources. The understanding of processes driving improvements or deterioration in natural resources remains constrained due to the disparate concepts and terminologies used across scientific disciplines to describe complex socio-ecological systems. Without a unified framework to synthesize findings, isolated knowledge fails to accumulate. Historically, prevailing theory assumed that resource users would not autonomously organize to safeguard their resources, necessitating government intervention for solutions. However, research across various disciplines has shown that certain government policies may hasten resource degradation, while some resource users have actively worked toward achieving sustainability by investing their efforts and time. Scientific studies advocate for a social-ecological systems approach to protected area management. This involves considering the interactions between ecosystems and human communities, fostering collaboration, and integrating local knowledge [69]. Protected areas and reserves are integral to sustainable forest land management, and their effectiveness relies on scientific principles and ongoing research. By combining conservation biology, landscape ecology, and adaptive management strategies, protected areas contribute significantly to biodiversity conservation and the sustainable use of forest resources.

3.2 Habitat restoration and connectivity

Habitat restoration and connectivity are vital components of sustainable forest land management, contributing to biodiversity conservation, ecosystem resilience, and overall landscape health. Scientifically guided restoration practices aim to repair ecosystems that have been degraded or fragmented, while enhancing connectivity to ensures the movement of species across landscapes. Scientifically informed habitat restoration aims to recreate and rehabilitate degraded ecosystems, promoting the recovery of biodiversity. Maintaining ecological connectivity through wildlife corridors is crucial for facilitating the movement of species across fragmented landscapes [70].

Scientific understanding of ecological succession informs habitat restoration. Restoration ecology principles involve mimicking natural processes to accelerate the

recovery of ecosystems. Studies highlight the importance of selecting native species, understanding soil dynamics, and considering the interactions between different trophic levels [71]. Genetic diversity is a critical consideration in habitat restoration to ensure the long-term viability of restored populations. Scientific research emphasizes the importance of maintaining genetic diversity to enhance adaptive capacity and resilience [72]. Scientifically informed habitat restoration involves the selection of target species based on ecological requirements and their role in the overall ecosystem. This approach ensures that restored habitats support diverse assemblages of plants, animals, and microorganisms [63].

Adaptive management principles are integral to habitat restoration, allowing for adjustments based on continuous monitoring and assessment. Scientifically guided adaptive management ensures that restoration efforts are responsive to changing environmental conditions [71]. Scientifically guided reforestation and afforestation efforts aim to restore degraded or deforested areas. Studies contribute to selecting appropriate tree species, understanding soil conditions, and evaluating the impacts of restoration on biodiversity [73].

Scientific research plays a crucial role in wetland restoration by informing hydrological considerations, vegetation selection, and monitoring strategies. Restoration of wetlands contributes to water purification, flood control, and habitat creation [74]. The findings from meticulously crafted studies indicate that corridors serve as valuable conservation mechanisms. Those advocating for the destruction of the remaining natural connectivity should be tasked with demonstrating that such actions will not detrimentally impact the target populations. Scientific approaches to landscape connectivity involve identifying and preserving corridors that facilitate the movement of species between fragmented habitats. Studies focus on the design and effectiveness of corridors in maintaining biodiversity and promoting gene flow [75]. Understanding the movement ecology of wildlife is crucial for connectivity planning. Scientific research utilizes techniques such as GPS tracking and habitat modeling to assess the spatial requirements of species and inform the design of corridors [76]. Invasive species pose challenges to habitat restoration efforts. Scientific studies contribute to understanding the impacts of invasive species on restored ecosystems and developing strategies to manage their spread [71]. Climate change adds complexity to habitat restoration. Scientific research explores strategies for adapting restoration practices to changing climatic conditions, such as selecting climate-resilient species and considering future climate scenarios [77].

Increasingly, translocations are being suggested as a method to preserve biodiversity, especially in the conservation of threatened and keystone species. The objective is to sustain biodiversity and ecosystem functionality amidst the challenges of habitat fragmentation and climate change. Incorporating evolutionary genetic aspects into translocation strategies is crucial, yet there is often ambiguity regarding concepts and objectives in this regard. Advancements in genetic technologies offer opportunities for enhancing the genetic diversity of restored populations. Scientific research explores techniques such as assisted gene flow and genetic engineering to improve the resilience of restored ecosystems [78]. Scientifically guided research increasingly incorporates socio-ecological considerations in habitat restoration. This involves understanding the social and economic dimensions of restoration projects, engaging local communities, and integrating traditional ecological knowledge [71]. Habitat restoration and connectivity are essential strategies in sustainable forest land management, driven by scientific principles and ongoing research. By integrating ecological understanding, adaptive management, and innovative techniques, these practices contribute to the resilience and health of forest ecosystems.

4. Various actions undertaken for sustainable forest land management

Sustainable management of forested lands entails adopting a comprehensive and equitable strategy for utilizing and conserving forest ecosystems. This approach aims to address present requirements while safeguarding their sustainability for future generations. Various actions are undertaken under this umbrella to promote ecological health, biodiversity conservation, and the sustainable use of forest resources. Here are key components and actions associated with sustainable forest land management:

4.1 Forest planning and governance

4.1.1 Scientific assessment

Scientific assessment is a crucial component of sustainable forest land management, providing a systematic and evidence-based approach to understanding the ecological, biological, and environmental aspects of forest ecosystems. These assessments serve as a foundation for informed decision-making, guiding management strategies that aim to balance human needs with the conservation of biodiversity and ecosystem health. There is a need to conduct comprehensive assessments of forest ecosystems to understand their ecological characteristics, biodiversity, and potential threats.

Scientific assessments in sustainable forest land management are iterative processes that involve the integration of various scientific disciplines, stakeholder input, and adaptive management principles. The aim is to develop a comprehensive understanding of forest ecosystems, inform sustainable management practices, and contribute to the long-term conservation of biodiversity and ecosystem services.

4.1.2 Stakeholder engagement

Stakeholder engagement is a fundamental and integral aspect of sustainable forest land management. It involves active involvement, collaboration, and communication with various individuals, groups, and organizations that have an interest or stake in the management and use of forest resources. Effective stakeholder engagement is essential for ensuring that diverse perspectives are considered, fostering inclusive decision-making, and promoting the long-term sustainability of forest ecosystems. Incorporating a variety of viewpoints necessitates engaging local communities, indigenous populations, and other stakeholders in the decision-making process.

Stakeholder engagement is an ongoing and dynamic process that evolves as forest management priorities, challenges, and stakeholders' interests change over time. It is an essential element of adaptive management, allowing for continuous learning and improvement in sustainable forest land management practices.

4.2 Biodiversity conservation

4.2.1 Protected areas and reserves

Protected areas and reserves play a crucial role in sustainable forest land management by conserving biodiversity, protecting critical habitats, and maintaining ecosystem services. These areas are designated and managed with the primary goal of

preserving natural ecosystems and their associated flora and fauna. Protected areas and reserves are cornerstones of sustainable forest land management, embodying a balance between conservation and the responsible use of forest resources. Strategic planning, community engagement, and adaptive management are essential for their continued success in preserving biodiversity and supporting ecosystem health.

4.2.2 Habitat restoration

Habitat restoration is a critical component of sustainable forest land management, focusing on the rehabilitation and improvement of ecosystems that have been degraded, damaged, or altered. This process aims to enhance biodiversity, ecosystem functionality, and overall ecological health. Habitat restoration in forests involves a combination of ecological knowledge, scientific research, and active management strategies. Habitat restoration is a dynamic and ongoing process that requires collaboration among scientists, land managers, local communities, and various stakeholders. Continuous monitoring and adaptive management are essential to ensure the long-term success of restoration initiatives.

4.3 Timber harvesting practices

4.3.1 Selective logging

Selective logging, also known as selective cutting or selective timber harvesting, is a forestry practice that involves the removal of specific trees or groups of trees from a forest, while leaving the majority of the stand intact. This approach contrasts with clear-cutting, where all trees in an area are cut down. Selective logging aims to achieve sustainable timber extraction while minimizing the ecological impact on the forest ecosystem. Selective logging represents a compromise between the demand for timber resources and the need to conserve forest ecosystems. When implemented with careful planning, adherence to sustainable forestry principles, and ongoing monitoring, selective logging can be a valuable tool in achieving a balance between resource extraction and ecosystem conservation. Continuous research and adaptive management practices contribute to the refinement and improvement of selective logging techniques.

4.3.2 Silvicultural practices

Silviculture involves managing the establishment, growth, composition, health, and quality of forests to achieve particular goals. Silvicultural practices are essential components of sustainable forest land management, aiming to balance ecological, social, and economic goals. These practices involve the manipulation of forest stands to enhance timber production, biodiversity conservation, and ecosystem services.

Silvicultural practices are diverse and adaptable, reflecting the complexity of managing forests for various ecological, economic, and social goals. Sustainable forest management requires a holistic approach that considers the specific characteristics of each forest ecosystem, local communities, and broader environmental objectives. The integration of science, technology, traditional knowledge, and adaptive management principles is essential for promoting resilience and long-term sustainability in forested landscapes.

4.4 Fire management

4.4.1 Controlled burns

Controlled burns, also known as prescribed fires or controlled fire management, are deliberate and carefully planned fires that are intentionally ignited under controlled conditions. These fires are used as forestry and land management tools to achieve specific ecological, silvicultural, or land-use objectives. Controlled burns play a crucial role in maintaining ecosystem health, reducing the risk of wildfires, and promoting biodiversity.

Controlled burns are valuable tools in the management of forests and ecosystems, providing numerous benefits for ecological health, wildfire risk reduction, and biodiversity conservation. However, their successful implementation requires meticulous planning, adherence to safety standards, and consideration of environmental and community factors. Integrating controlled burns into a broader strategy of adaptive forest management contributes to the overall resilience and sustainability of forested landscapes.

4.4.2 Wildfire risk assessment

Wildfire risk assessment is a critical component of forest land management, helping to identify and evaluate potential risks associated with wildfires in a given area. This process involves analyzing various factors, including environmental conditions, vegetation types, topography, and human activities, to assess the likelihood and potential impacts of wildfires. Wildfire risk assessment is a multidimensional process that integrates scientific data, community input, and proactive management strategies. By understanding the complex interactions of environmental, social, and ecological factors, land managers can develop effective strategies to mitigate wildfire risks, protect communities, and foster ecosystem resilience. The ongoing challenges associated with dynamic conditions and human behavior highlight the importance of adaptive management and community engagement in wildfire risk reduction efforts.

4.5 Carbon sequestration and climate change mitigation

4.5.1 Reforestation and afforestation

Reforestation and afforestation are crucial components of sustainable forest land management, contributing to biodiversity conservation, carbon sequestration, and ecosystem restoration. These practices involve the establishment or restoration of forest cover in areas where it has been depleted or lost. Reforestation refers to the process of replanting trees in areas that were once forested but have been deforested or degraded. This practice aims to restore forest cover, enhance biodiversity, and provide various ecological and socioeconomic benefits. Afforestation involves the establishment of forests in areas where there was no forest cover previously, such as barren lands, degraded landscapes, or agricultural fields. It is a proactive measure to increase forested areas and address issues like soil degradation and desertification. Reforestation and afforestation are integral components of sustainable forest land management, addressing deforestation, promoting biodiversity, and contributing to climate change mitigation. While these practices come with challenges, careful planning, adaptive management, and community involvement can enhance their success and contribute to the overall health and resilience of ecosystems.

4.5.2 Carbon markets

Carbon markets, alternatively referred to as emissions trading systems or cap-and-trade programs, are mechanisms crafted to diminish greenhouse gas (GHG) emissions by implementing a cost on carbon. These markets establish economic motives for enterprises and industries to curtail their carbon footprint by attributing a monetary worth to the privilege of emitting a specific quantity of carbon dioxide (or other greenhouse gases). Carbon markets serve a pivotal function in the worldwide endeavor to combat climate change by furnishing economic inducements for emission reduction and promoting sustainable land management practices. While they offer opportunities to fund projects that sequester carbon and promote biodiversity, challenges such as market volatility and equity concerns need to be carefully addressed. The evolution and effectiveness of carbon markets depend on ongoing regulatory developments, technological advancements, and the commitment of businesses and governments to reduce greenhouse gas emissions.

There are generally two categories of carbon markets: compliance and voluntary. Compliance markets arise due to national, regional, and/or international policies or regulatory mandates. Voluntary carbon markets, whether domestic or international, involve the issuance, purchase, and sale of carbon credits on a voluntary basis. Presently, the bulk of voluntary carbon credits originate from private entities involved in carbon projects or governments implementing programs certified by carbon standards, which produce emission reductions and/or removals.

4.6 Invasive species management

4.6.1 Early detection and eradication

An invasive species particularly of forest ecosystem is referred as Forest Invasive Species (FIS). FIS are directly related to the forestry and serious threat to forest cover. FIS can remove native species, food, and forest cover. Human trade, tourism, transport, and travel have enhanced the spread of FIS. For example, Lantana has invaded forest lands, Parthenium in agricultural and forestry areas and Eupatorium in mountain ecosystems, etc. FIS are highly significant in the national context. The bioclimatic conditions of India have been congenial, and alien species have invaded the various landscapes and ecosystems. There is a lacuna in the knowledge of the biology, geographical distribution, genetic diversity, and inter-crossing (hybridizing) potentials of the forest invasive alien species. The entry of blue gum chalcid wasp, Leptocybe invasa, in India has threatened eucalyptus throughout the country. The present chapter contemplates and describes succinctly the invasive alien species (IAS), with special emphasis on FIS in India. Further, it also highlights the impacts of FIS in forestry and forest cover, their prevention, current position, measures to control FIS, categorization of invasiveness, environmental impact assessment, and possible management of FIS to save native forests as well as the environment.

Invasive alien species (FIS) alter both the function and structure of ecosystems, impacting communities, habitats, and species within protected areas and beyond. Their influence extends to livelihoods and poverty reduction, directly or indirectly affecting ecosystem services, sustainable biodiversity utilization, and cultural and heritage values. The information in this respect has been compiled at a global level [79]. A cumulative count of 326 invasive alien species (IAS) has been documented across 487 protected area sites, spanning 106 countries across Asia, Africa, South and

Central America (including Mexico and the Caribbean), and Europe. Among these, approximately 43 IAS species have been identified within protected areas in Asia [80]. These species are *Acacia mearnsii, Acacia nilotica, Adhatoda vasica, Ageratum conizoides, Annona glabra, Aulacaspis yasumatsui, Axis axis, Bubalus bubalis, Cervus timorensis, Cervus unicolor, Chitala ornate, Chromolaena odorata, Cirsium vulgare, Clerodendron viscosum, Clidemia hirta, Dioscorea sanibariensis, Egeria densa, Eichhornia crassipes, Elephas maximus, Eupatorium* sp., *Imperata cylindrica, Lantana camara, Micania micrantha, Mikania* sp., *Mimosa diplotricha, Mimosa invisa, Mimosa pigra, Mimosa pudica, Muntiacus muntjak, Najas marinus, Nelumbo nucifera, Oncorhynchos mykiss, Pomacea* sp., *Opuntia dillennii, Parthenium hysterophorus, Procyon lotor, Prosopis juliflora, Salvinia molesta, Salvinia* sp., *Spartina* sp., *Sus scrofa, Tiliacora acuminata, and* Ulex europaeus.

4.6.2 Research and monitoring

Research and monitoring of invasive species are fundamental components of effective invasive species management. These activities provide essential data for understanding the biology, ecology, and impacts of invasive species, as well as informing strategies for their control and prevention. Research and monitoring are indispensable components of invasive species management, providing the foundation for understanding, preventing, and mitigating the impacts of invasive species. Integrating research findings into monitoring programs and management actions ensures a dynamic and adaptive approach to addressing this global challenge. Collaboration among scientists, managers, policymakers, and communities is essential for developing effective strategies and fostering resilience in ecosystems threatened by invasive species.

4.7 Community-based conservation

4.7.1 Community forest management

Community forest management (CFM) is a forest management approach that engages local communities in decision-making, planning, and the sustainable utilization of forest resources through active participation. This collaborative and inclusive model aims to balance ecological conservation with the socioeconomic needs of the communities residing in or near forested areas. Community forest management is a holistic and participatory approach that recognizes the interconnectedness of ecological and social systems. When implemented effectively, CFM can contribute to sustainable development, biodiversity conservation, and the well-being of local communities. Overcoming challenges requires a combination of legal support, capacity building, and collaboration among governments, communities, and other stakeholders.

4.7.2 Capacity building

Capacity building refers to the process of enhancing an individual's, communities, or organization's ability to perform effectively, efficiently, and sustainably. In the context of sustainable forest land management, capacity building plays a crucial role in empowering individuals and communities to understand, plan, and implement practices that promote the conservation and sustainable use of forest resources. Capacity building is a cornerstone in fostering sustainable forest land management practices.

By empowering communities with knowledge, skills, and resources, capacity-building initiatives contribute to the conservation of biodiversity, the promotion of sustainable livelihoods, and the resilience of ecosystems. Tackling the capacity-building challenges demands a cooperative and flexible strategy, engaging a wide array of stakeholders dedicated to the enduring welfare of forests and the communities reliant upon them.

4.8 Remote sensing and GIS

4.8.1 Monitoring and surveillance

Monitoring and surveillance are integral components of sustainable forest land management. These processes involve systematic observation, measurement, and assessment of various ecological, social, and economic parameters to track changes in forest conditions, identify potential threats, and inform adaptive management strategies. Effective monitoring and surveillance contribute to informed decision-making, early detection of issues, and the promotion of sustainable practices. Monitoring and surveillance are indispensable tools in the sustainable forest land management toolbox. By systematically collecting and analyzing data on ecological and social parameters, these practices contribute to effective decision-making, early threat detection, and the conservation of forest ecosystems. Overcoming challenges requires collaboration, capacity building, and the integration of both traditional knowledge and technological advancements.

4.8.2 Data-driven decision making

Data-driven decision making is a methodical approach that entails utilizing pertinent and trustworthy data to shape and direct the decision-making process. In the context of sustainable forest land management, leveraging data-driven decision-making is crucial for making informed choices that align with conservation goals, address emerging challenges, and optimize the use of limited resources. Data-driven decision-making is a powerful tool in the sustainable forest land management toolkit. By harnessing relevant and high-quality data, decision-makers can navigate the complexities of forest ecosystems, address challenges, and contribute to long-term conservation goals. Overcoming challenges requires collaboration, investment in technology and capacity building, and a commitment to transparency in the decision-making process.

4.9 Adaptive management strategies

4.9.1 Learning and feedback loops

Learning and feedback loops are critical components of adaptive management in the context of sustainable forest land management. These processes involve continuously acquiring knowledge, adjusting strategies based on that knowledge, and incorporating feedback to enhance decision-making and conservation efforts. Learning and feedback loops are essential for maintaining the dynamism required in sustainable forest land management. By continuously learning from experiences, adapting strategies, and incorporating feedback, stakeholders can navigate the complexities of forest ecosystems and contribute to long-term conservation success. Overcoming challenges involves fostering open communication, addressing resource constraints, and cultivating a culture of adaptive management.

4.9.2 Scenario planning

Scenario planning is a strategic management technique that entails envisioning and preparing for various potential future scenarios. In the context of sustainable forest land management, scenario planning can help stakeholders anticipate and respond to a range of potential future conditions, uncertainties, and challenges. Scenario planning is a valuable tool for navigating the uncertainties and complexities associated with sustainable forest land management. By considering a range of plausible futures, stakeholders can develop robust strategies that enhance adaptive capacity and resilience. Overcoming challenges requires a commitment to collaboration, ongoing learning, and a willingness to adapt strategies based on evolving scenarios.

4.10 Socioeconomic benefits

4.10.1 Ecotourism

Ecotourism is a sustainable form of tourism that focuses on responsible travel to natural areas, with the goal of conserving the environment, respecting local cultures, and promoting the well-being of local communities. In the context of sustainable forest land management, ecotourism can play a significant role in generating economic benefits, promoting conservation awareness, and providing incentives for the preservation of forest ecosystems. Ecotourism, when implemented thoughtfully and sustainably, can be a powerful tool for supporting both conservation efforts and local communities. Balancing the economic benefits of ecotourism with environmental and cultural considerations requires careful planning, community engagement, and effective management.

4.10.2 Non-timber forest products

Non-Timber Forest Products (NTFPs) encompass a diverse array of natural resources sourced from forests, excluding traditional timber, and wood products. These products can include plants, fungi, animals, and various forest-derived materials that serve both subsistence and commercial purposes. NTFPs play a crucial role in supporting the livelihoods of many communities, contributing to biodiversity conservation, and promoting sustainable forest management. Non-Timber Forest Products (NTFPs) are crucial contributors to the sustainable stewardship of forests, providing a multitude of economic, social, and environmental advantages. Balancing the utilization of NTFPs with conservation goals requires thoughtful management practices, community engagement, and the development of supportive policies and markets.

4.11 Research and innovation

4.11.1 Scientific research

Scientific research in the context of sustainable forest land management is essential for advancing our understanding of ecosystems, biodiversity, and the impact of management practices. This plays a pivotal role in facilitating evidence-based decision-making, formulating sustainable strategies, and tackling the intricate challenges associated with forest conservation. Scientific research is fundamental to advancing our understanding of sustainable forest land management and addressing

the challenges faced by forest ecosystems. Through rigorous and interdisciplinary approaches, researchers can contribute valuable insights that guide conservation efforts, promote sustainable practices, and ensure the resilience of forests in the face of global environmental changes.

4.11.2 Technological innovation

Technological innovation plays a pivotal role in advancing sustainable forest land management, offering new tools and solutions to address complex challenges, enhance efficiency, and promote conservation efforts. Innovations should align with sustainable principles, considering ecological, social, and economic aspects of forest management. Technologies should be adaptable to different environmental contexts and forest types, allowing for widespread applicability. Involve local communities in the development and adoption of technologies to ensure relevance and acceptance. Encourage collaboration between technology developers, ecologists, social scientists, and forest managers to create holistic solutions. Technological innovation holds tremendous potential to transform sustainable forest land management, offering solutions to complex challenges and promoting more effective conservation efforts. Overcoming challenges requires collaboration, investment in education and training, and a commitment to ensuring that technological advancements align with sustainable principles.

4.12 Education and outreach

4.12.1 Public awareness campaigns

Public awareness campaigns are crucial for promoting understanding, garnering support, and encouraging responsible behaviors in the context of sustainable forest land management. These campaigns aim to inform the public about the importance of forests, the challenges they face, and the role individuals and communities can play in conservation efforts. Public awareness campaigns are powerful tools for fostering a deeper understanding of sustainable forest land management, encouraging responsible behaviors, and building a collective commitment to conservation. Successful campaigns integrate education, engagement, and cultural sensitivity while addressing the specific challenges and opportunities of the target audience.

4.12.2 Environmental education

Environmental education is a crucial component of promoting awareness, understanding, and action toward sustainable forest land management. It involves providing individuals with knowledge about the environment, fostering a sense of responsibility, and empowering them to make informed decisions that contribute to the conservation of forests. Environmental education plays a pivotal role in building a foundation of knowledge and values that support sustainable forest land management. Overcoming challenges requires a multifaceted approach, including collaboration between educational institutions, communities, and policymakers. Environmental education is a cornerstone in the pursuit of sustainable forest land management. By combining scientific rigor with community engagement and policy advocacy, we can create a more informed and empowered society capable of addressing the complex challenges associated with forest conservation and management.

4.13 Certification programs

4.13.1 Forest Stewardship Council

The Forest Stewardship Council (FSC) is a global non-profit organization dedicated to advocating responsible forest management practices. Since its establishment in 1993, the FSC has crafted an internationally acknowledged certification framework for forestry and wood products, guaranteeing the environmentally, socially, and economically sustainable management of forests. The Forest Stewardship Council is instrumental in advocating responsible forest management practices on a global scale. FSC certification provides a recognizable and trusted standard for consumers and businesses committed to supporting sustainability. While facing challenges, the FSC continues to work toward improving forest management, fostering environmental conservation, and promoting social responsibility within the forest industry.

5. Types of interventions used for sustainable forest land management

Sustainable forest land management involves a range of interventions aimed at balancing the ecological, economic, and social dimensions of forest ecosystems. These measures are crafted to safeguard the enduring health and productivity of forests, while simultaneously addressing the requirements of both current and forthcoming generations. Here are some key types of interventions used in sustainable forest land management:

5.1 Silvicultural practices

Selective Logging: Careful harvesting of specific trees while preserving the overall forest structure.

Agroforestry: Integrating trees with agricultural crops to enhance biodiversity and provide additional income sources.

Afforestation and Reforestation: Planting trees in deforested or degraded areas to restore and expand forest cover.

5.2 Ecosystem-based management

Prescribed Burns: Controlled burning to reduce fuel loads, prevent wildfires, and promote the regeneration of fire-adapted species.

Wildlife Habitat Management: Creating and maintaining habitats for diverse plant and animal species.

Water Resource Protection: Ensuring that forest management practices do not negatively impact water quality and availability.

5.3 Biodiversity conservation

Protected Areas: Establishing reserves and protected zones to safeguard critical habitats and biodiversity.

Invasive Species Management: Controlling and eradicating invasive species that threaten native flora and fauna.

Genetic Conservation: Preserving the genetic diversity of tree species through seed banks and genetic reserves.

5.4 Community involvement and social forestry

Community Forest Management: Involving local communities in decision-making processes and benefit-sharing.

Capacity Building: Providing training and education to local communities on sustainable forest management practices.

Forest Certification Programs: Promoting responsible forestry through certification schemes such as FSC (Forest Stewardship Council).

5.5 Policy and governance

Legal Frameworks: Implementing and enforcing laws and regulations that govern forest management.

Land-Use Planning: Developing comprehensive plans to allocate and manage land for various uses, including forestry.

International Collaboration: Engaging in global initiatives and agreements to address transboundary issues and promote sustainable practices.

5.6 Technological innovations

Remote Sensing and GIS: Using technology to monitor forest health, detect changes, and plan interventions.

Precision Forestry: Applying technology to optimize resource use and minimize environmental impact in forestry operations.

Scientific research plays a crucial role in evaluating the effectiveness of these interventions. Studies often assess ecological indicators, economic viability, and social impacts to provide evidence-based recommendations for sustainable forest land management. Additionally, ongoing monitoring and adaptive management are essential components to ensure that interventions align with changing environmental conditions and societal needs [81–83].

6. Comparative analysis of different types of interventions

A comprehensive comparison of different types of interventions used for sustainable forest land management requires an evaluation across various dimensions, including ecological, economic, and social aspects. A comparative analysis of key interventions based on these criteria:

6.1 Silvicultural practices

6.1.1 Selective logging

In a study area with diverse tree species, a carefully managed selective logging program may demonstrate efficacy by maintaining biodiversity and supporting valuable timber species. Implementation could involve maintaining minimum cutting diameters, using reduced-impact logging techniques, and ensuring regeneration of harvested areas.

Ecological Impact: This may result in habitat fragmentation and biodiversity loss.

Economic Impact: Provides revenue but needs careful planning to avoid overharvesting.

Social Impact: Can impact local communities and indigenous groups negatively.

6.1.2 Agroforestry

In regions where traditional agriculture and forestry coexist, an agroforestry model might show efficacy by improving soil fertility, providing alternative income sources for local communities, and enhancing overall landscape resilience. The integration of fruit trees or coffee plants within forested areas could serve as examples.

Ecological Impact: Enhances biodiversity and soil fertility.

Economic Impact: Diversifies income sources for communities.

Social Impact: Fosters community engagement and involvement in land management.

6.1.3 Afforestation and reforestation

In areas affected by deforestation or degradation, successful afforestation and reforestation efforts could be seen through restored ecosystems, increased carbon sequestration, and improved water quality. The choice of native tree species and community involvement in planting campaigns are crucial factors for efficacy.

Ecological Impact: Restores ecosystems and sequesters carbon.

Economic Impact: Provides long-term benefits but requires initial investment.

Social Impact: Creates employment and promotes environmental awareness.

6.2 Ecosystem-based management

6.2.1 Prescribed burns

In fire-prone regions, the use of prescribed burns could effectively reduce the risk of uncontrolled wildfires, promote the regeneration of fire-adapted species, and protect communities from fire-related hazards. Adequate planning and community involvement are essential for success.

Ecological Impact: Promotes fire-adapted species and reduces wildfire risk.

Economic Impact: Can be cost-effective in preventing uncontrolled fires.

Social Impact: Requires careful communication due to perceived risks.

6.2.2 Wildlife habitat management

In a study area with diverse fauna, wildlife habitat management initiatives might demonstrate efficacy by supporting endangered species, promoting biodiversity, and enhancing ecotourism opportunities. Restoration of degraded habitats and the creation of wildlife corridors could be key strategies.

Ecological Impact: Preserves biodiversity and supports ecosystem health.

Economic Impact: Can enhance ecotourism opportunities.

Social Impact: Fosters a sense of environmental stewardship.

6.2.3 Water resource protection

In regions where forests play a crucial role in watershed management, interventions to protect water resources could prove effective by maintaining stream flow, preserving aquatic habitats, and ensuring a clean water supply for downstream communities.

Ecological Impact: Safeguards water quality and aquatic habitats.
Economic Impact: Protects water supply for downstream users.
Social Impact: Benefits communities dependent on forest water sources.

6.3 Biodiversity conservation

6.3.1 Protected areas

Creating and efficiently managing protected areas in ecologically fragile regions can demonstrate effectiveness by conserving crucial habitats, protecting endangered species, and fostering scientific research and ecotourism [84].
Ecological Impact: Safeguards critical habitats and biodiversity.
Economic Impact: Tourism and research opportunities.
Social Impact: Balances conservation with indigenous land rights.

6.3.2 Invasive species management

A study area dealing with invasive species could demonstrate efficacy through successful control measures, preventing the spread of non-native plants or pests that threaten the health of the forest ecosystem.
Ecological Impact: Preserves native species and ecosystems.
Economic Impact: Prevents economic losses associated with invasive species.
Social Impact: This may require public cooperation in control efforts.

6.3.3 Genetic conservation

In regions with unique or endangered tree species, genetic conservation efforts could prove effective by preserving the genetic diversity of key species. Seed banks and genetic reserves might be established to ensure the resilience of local ecosystems.
Ecological Impact: Preserves genetic diversity for species resilience.
Economic Impact: Safeguards against loss of valuable genetic resources.
Social Impact: Ensures continuity of traditional uses of plant materials.

6.4 Community involvement and social forestry

6.4.1 Community forest management

In areas where local communities actively participate in decision-making, community forest management initiatives may showcase efficacy by fostering sustainable practices, providing economic benefits, and strengthening community bonds.
Ecological Impact: Can enhance conservation through local knowledge.
Economic Impact: Directly benefits local communities economically.
Social Impact: Empowers communities and strengthens social cohesion.

6.4.2 Capacity building

Efforts to enhance the capacity of local communities through education and training programs could be effective in promoting sustainable forest management practices and empowering communities to take an active role in conservation.
Ecological Impact: Enhances understanding of sustainable practices.

Economic Impact: Supports skill development for sustainable livelihoods.
Social Impact: Fosters a sense of ownership and responsibility.

6.4.3 Forest certification programs

Implementation of forest certification programs could demonstrate efficacy by ensuring responsible management practices, improving market access for certified products, and signaling a commitment to sustainability.
Ecological Impact: Encourages responsible forest management.
Economic Impact: Enhances market access for certified products.
Social Impact: Demonstrates commitment to sustainable practices.

6.5 Policy and governance

6.5.1 Legal frameworks

A study area with well-defined and enforced legal frameworks may exhibit efficacy in sustainable forest management by regulating land use, preventing illegal logging, and safeguarding the rights of local communities.
Ecological Impact: Depends on the stringency of regulations.
Economic Impact: Can drive sustainable practices but may face enforcement challenges.
Social Impact: Influences land-use decisions and community rights.

6.5.2 Land-use planning

Effective land-use planning, involving stakeholders and considering ecological sensitivities, could demonstrate efficacy by minimizing conflicts, optimizing resource allocation, and promoting balanced development.
Ecological Impact: Balances competing land-use demands.
Economic Impact: Influences investment and development patterns.
Social Impact: Requires participatory approaches for inclusivity.

6.5.3 International collaboration

Collaboration between countries or regions may show efficacy in addressing transboundary issues such as deforestation, climate change, and biodiversity loss. Joint initiatives, knowledge exchange, and shared resources can contribute to sustainable forest management.
Ecological Impact: Addresses global challenges like deforestation.
Economic Impact: Enhances access to international funding and expertise.
Social Impact: Encourages knowledge exchange and cooperative initiatives.

6.6 Technological innovations

6.6.1 Remote sensing and geographic information system (GIS)

The application of remote sensing and GIS technologies can exhibit effectiveness by enabling real-time monitoring of changes in forest cover, facilitating early detection of disturbances, and assisting in the planning of precise interventions [85].

Ecological Impact: Provides real-time monitoring for timely interventions.
Economic Impact: Enhances efficiency in resource management.
Social Impact: Requires capacity building for effective use.

6.6.2 Precision forestry

In areas where precision forestry technologies are adopted, efficacy can be seen through optimized resource use, reduced environmental impact, and increased efficiency in logging operations.

Ecological Impact: Minimizes environmental impact through targeted interventions.

Economic Impact: Optimizes resource use and reduces waste.

Social Impact: May require training for workers in new technologies.

While these examples provide a general overview, the efficacy of interventions in sustainable forest land management is highly context-specific. Successful outcomes depend on the unique characteristics of the study area, active engagement of local communities, adaptive management strategies, and ongoing monitoring and research to assess the long-term impacts of interventions [82, 84]. In conclusion, the effectiveness of interventions varies based on the specific context, ecosystem characteristics, and the involvement of local communities. A holistic approach that considers ecological integrity, economic viability, and social equity is crucial for successful sustainable forest land management [86–88].

7. Efficacy of interventions

The efficacy of interventions in developing sustainable forest land management involves considering multiple dimensions, including ecological, economic, and social aspects. Evaluating the effectiveness of these interventions in enhancing the long-term health and resilience of forest ecosystems, while also fulfilling the requirements of both current and future generations, is paramount.

The efficacy of interventions in sustainable forest land management is context-dependent. Integrated approaches that consider ecological, economic, and social aspects, along with adaptive management, are likely to yield the most successful and sustainable outcomes. Ongoing research and monitoring are essential to continually improve and adapt interventions based on evolving knowledge and conditions [89–91].

8. Restoration of degraded forest land

Revitalizing degraded forest lands is a vital aspect of sustainable forest land management, with the goal of rehabilitating ecosystems adversely affected by human activities like logging, agriculture, or mining. Scientifically informed restoration strategies are essential to ensure the effectiveness and long-term success of such efforts. Rehabilitating degraded forest land is a multifaceted and intricate process that necessitates an approach grounded in scientific knowledge. This involves understanding the underlying causes of degradation, implementing appropriate interventions, and monitoring the success of restoration efforts. The scientific aspects of restoring degraded forest land, covering key principles, and methodologies.

8.1 Ecological assessment and planning

8.1.1 Scientific understanding

Ecological restoration is frequently employed to counteract environmental degradation resulting from human activities. Yet, the systematic evaluation of restoration efforts' effectiveness in enhancing both biodiversity and ecosystem services provision has been lacking. A meta-analysis of 89 restoration assessments conducted across various ecosystem types' worldwide reveals that ecological restoration boosted biodiversity provision by 44% and ecosystem services provision by 25%. However, these values remained lower in restored ecosystems compared to intact reference ecosystems. The study found a positive correlation between increases in biodiversity and ecosystem service measures following restoration efforts. Before initiating restoration, a thorough ecological assessment is crucial. This involves studying soil quality, vegetation composition, hydrology, and the impact of past disturbances. Scientific assessments help identify the root causes of degradation and inform appropriate restoration strategies [92].

8.1.2 Adaptive planning

A dynamic, adaptive management plan is essential. This plan should consider the resilience of the ecosystem, potential climate change impacts, and the need for flexible strategies based on ongoing scientific monitoring [93].

8.2 Native species selection and seed sourcing

8.2.1 Biodiversity conservation

The decline in forest biodiversity poses a significant threat to the functionality of forest ecosystems, including crucial activities, processes, and characteristics such as the decomposition of organic matter, soil nutrient cycling, and water retention. Consequently, this may diminish the forests' capacity to provide essential ecosystem services. Ecosystem services, defined as the benefits derived by people from ecosystems, are typically classified into four main categories. These encompass provisioning services such as food, water, timber, and fiber; regulating services that impact climate (e.g., through carbon sequestration), pollination, biological pest control, floods, disease control, waste management, and water quality; cultural services that offer recreational, esthetic, and spiritual benefits; and supporting services like soil formation, photosynthesis, and nutrient cycling.

Scientific evidence supports the use of native species in restoration projects. Native plants are adapted to local conditions, promoting biodiversity and ecosystem resilience. Seed sourcing from local populations helps maintain genetic diversity, ensuring adapted and robust plant communities [63, 94].

8.3 Soil remediation and erosion control

8.3.1 Scientific soil management

Soil remediation encompasses the handling of contaminants at a site to prevent harm to human health or the environment. This process includes identifying soils in need of remediation, establishing remedial objectives based on future land use, selecting and implementing remedial strategies, and monitoring outcomes.

Monitoring typically involves measuring contaminant concentrations, although biological tools can also be employed for this purpose.

Numerous soil remediation strategies, including soil washing, soil restoration, solidification, stabilization, excavation, and electro-remediation, have been investigated through both field trials and controlled environmental studies. Among these methods, the stabilization of on-site pollutants using organic amendments shows significant potential for cost-effective performance. The constant generation of large quantities of organic waste from animal and poultry industries to meet human consumption demands presents an opportunity for utilization in accordance with environmental regulations, including safe landfill disposal. These materials can serve as organic amendments for remediating metal-contaminated soils, alongside other agricultural and urban waste products. Their abundant availability and often low cost make them suitable for supplying the substantial volumes needed for remediation efforts across extensive agricultural areas [95].

Erosion poses a challenge on many disturbed sites before and during reclamation, as the soil lacks vegetation cover, leaving it vulnerable to wind and water erosion. To mitigate erosion on reclamation sites, contouring, amendments, and various materials like erosion control blankets and mulch can be utilized. Additionally, bioengineering techniques, which involve the use of plant materials, such as live staking (planting individual live wood cuttings into the soil), are employed. While many erosion control products prove highly effective, some can significantly increase the cost of the reclamation project.

Soil degradation is a common issue in degraded forest lands. Scientifically informed soil management techniques, such as organic matter addition and erosion control measures, are essential for restoring soil fertility and preventing further degradation [75].

8.4 Assisted natural regeneration and planting

8.4.1 Research-backed techniques

Assisted natural regeneration represents a straightforward, cost-effective restoration approach that can significantly improve the productivity and ecosystem functions of degraded forest lands. This method focuses on expediting, rather than substituting, natural successional processes by addressing obstacles to natural regeneration, such as soil degradation, competition with invasive species, and recurring disturbances like fire, grazing, and wood harvesting.

Assisted natural regeneration involves a variety of restoration interventions aimed at fulfilling various restoration goals and related policy objectives. The science and implementation of assisted natural regeneration constitute a relatively recent but expanding domain within restoration science, with numerous instances of successful applications emerging worldwide in recent years.

Assisted natural regeneration involves facilitating the recovery of ecosystems through natural processes. Scientific studies guide the implementation of effective techniques, such as gap creation, to allow natural seed dispersal and regeneration. Additionally, strategic planting of key species can accelerate recovery [75].

8.5 Ecosystem connectivity and landscape design

8.5.1 Landscape-level planning

Landscape ecological plans, which are land use plans rooted in ecological principles, are gaining traction, particularly in continental Europe and the United States.

This trend reflects the increasing maturity of landscape ecology, which is now not only informing theoretical frameworks but also providing practical solutions to real-world planning challenges. In countries with a long history of industrialization, the distinctive visual appeal and biodiversity have been significantly degraded due to various factors such as habitat destruction and fragmentation, intensive agriculture and forestry practices, river modifications, construction of transportation corridors, and industrial pollution. Additionally, more subtle effects stemming from pollution and nutrient transfers through air and water have also had notable impacts. Although conservation and development planning efforts have somewhat mitigated these pressures, there is a growing recognition of the necessity to restore the ecological integrity and visual harmony of both urban and rural areas through landscape-scale planning [96].

Landscape planning offers insights into the current attributes of the landscape and natural environment, which encompass the recognized nature or landscape potentials, their valuation, and sensitivity to impacts. It also examines the present and potential effects on these potentials, along with establishing objectives and guidelines for landscape and nature development. These serve as benchmarks against which proposed measures and development plans can be evaluated.

Using this information, landscape planning establishes assessment criteria for impact regulations and the aspect of environmental impact assessment focusing on the landscape and nature. In the initial stages of planning projects, landscape planning furnishes a framework for evaluating alternatives, such as determining the location of transportation corridors. Moreover, landscape planning forms the foundation for preliminary assessments of proposed projects, including those introduced after the landscape plan has been finalized [97].

Scientific approaches emphasize the importance of considering ecosystem connectivity at a landscape scale. This involves designing restoration projects that contribute to overall landscape connectivity, supporting gene flow, and enhancing biodiversity across larger areas [98].

8.6 Community involvement and social science integration

8.6.1 Social science integration

Local and indigenous communities frequently possess profound knowledge of the local ecosystems and demonstrate a vested interest in conserving ecosystem services. Areas under the stewardship of indigenous peoples and local communities often intersect with remaining intact ecosystems and experience lower rates of deforestation compared to unprotected regions. There are several compelling reasons why local communities are well-suited to oversee restoration initiatives. Drawing upon millennia of observation, experience, and management of forested lands, local communities possess invaluable insights. Moreover, their vested interest in restoring ecosystems from which they derive benefits further underscores their suitability for managing restoration efforts. Community-based institutions often exhibit greater efficacy compared to government policies or institutions due to their close engagement and ability to swiftly respond to environmental changes or threats. Indigenous and local communities frequently express profound spiritual and cultural connections to their lands, integral to their cultural and social identities, reflecting generations of ecological stewardship. These cultural and social bonds instill a commitment among local communities to value and sustainably manage their lands. This holistic understanding, recognizing that crucial ecosystem services such as food, water, and clean air hinge upon the health of functioning ecosystems,

serves as a driving force behind effective conservation and restoration efforts, ensuring a balanced approach to agricultural and resource utilization that prioritizes sustainable land management. Acknowledging cultural institutions can foster comprehension of restoration endeavors and enhance local engagement in these initiatives.

Integrating the objectives of ecological restoration with the active involvement of local communities is essential for achieving successful and sustainable ecosystem restoration [99]. These communities frequently rely directly on ecosystem services for their livelihoods and are particularly susceptible to land degradation. Consequently, the restoration of degraded habitats often holds crucial significance for the well-being of these communities, which are inherently motivated to restore the land that sustains their livelihoods. The knowledge and expertise of indigenous and local communities can serve as valuable resources in guiding and informing effective restoration initiatives. Traditional wisdom can help identify key species or areas pivotal to restoration endeavors [100, 101]. Furthermore, the longstanding relationship between local communities and the land can assist in defining natural benchmarks for species recovery, watershed management, and setting the objectives and targets of restoration initiatives [102].

The recognition and utilization of traditional knowledge are gaining prominence in the management of fire-prone regions. Indigenous peoples have demonstrated adeptness in fire management for centuries, employing controlled burns to reduce fuel loads and regulate wildlife and vegetation. For instance, the Australian Aborigines have upheld intricate land management practices, leveraging fire and native plant life cycles to ensure a consistent food supply throughout the year. These indigenous fire regimes and traditional knowledge are increasingly leveraged to restore native biodiversity and ecosystem functionality in restoration endeavors.

Similarly, local communities possess valuable insights into the processes of succession and regeneration inherent in habitat restoration. Drawing upon centuries of land management practices, including rotational farming, agroforestry, and land enclosures, these communities have developed effective strategies to prevent environmental degradation. These time-tested approaches offer valuable contributions to contemporary restoration efforts.

Scientifically informed restoration goes beyond ecological considerations. Integrating social science aspects, including traditional ecological knowledge and community preferences, is crucial for successful restoration. This collaboration ensures local support, promotes sustainable practices, and enhances the long-term success of restoration projects [103].

8.7 Monitoring and adaptive management

8.7.1 Scientific monitoring

Adaptive forest management is forward-thinking and seeks to maintain and enhance the functionality of specific forests to meet future demands for ecosystem services. It encompasses actions that adjust intact forests to changing growth and management conditions influenced by environmental factors and various economic considerations. Adaptive forest management and forest land restoration are not mutually exclusive; both prioritize ecosystem integrity and health, making them compatible and capable of integration within a multi-scale adaptive approach [104].

Robust monitoring based on scientific principles is essential for assessing the effectiveness of restoration efforts. This includes tracking changes in vegetation, soil quality, and biodiversity. Regular monitoring informs adaptive management,

allowing for adjustments based on scientific findings and changing conditions [63]. In conclusion, the restoration of degraded forest land requires a holistic, science-based approach that considers ecological, social, and economic factors. By integrating scientific principles, adaptive management, and community engagement, restoration efforts can contribute to the recovery of ecosystems, biodiversity conservation, and the sustainable use of natural resources [63, 73, 92, 94, 98, 103, 105].

9. Challenges and future directions

Despite the progress made in sustainable forest land management, challenges persist, including illegal logging, land-use change, and the impacts of climate change. Addressing these challenges requires international collaboration, effective policy frameworks, and ongoing scientific research to develop innovative solutions [105].

9.1 Challenges in sustainable forest land management

9.1.1 Climate change impact

Climate change has significant and multifaceted impacts on forest ecosystems, affecting their structure, composition, and functioning. The impacts of climate change present hurdles for the sustainable management of forested lands, necessitating well-informed approaches to both mitigate and adapt to these shifts. Climate change presents substantial obstacles to sustainable forest management. Shifts in precipitation patterns, rising temperatures, and the heightened frequency or intensity of extreme weather events have the potential to disrupt forest ecosystems, resulting in alterations to species composition, heightened susceptibility to pests and diseases, and shifts in wildfire dynamics [15].

9.1.2 Invasive species

Invasive species pose a significant threat to forest ecosystems, biodiversity, and sustainable forest land management. When introduced into unfamiliar environments, these non-native species have the capacity to outcompete indigenous flora and fauna, disrupt ecological processes, and degrade natural habitats. Scientific research and management strategies are essential to understanding and mitigating the impacts of invasive species on forests. The introduction and spread of invasive species threaten forest ecosystems by outcompeting native species, disrupting ecological processes, and altering habitat structure. Managing and controlling invasive species is a persistent challenge in sustainable forest land management [106].

9.1.3 Human-wildlife conflict

As human populations encroach upon forested areas, conflicts between humans and wildlife can escalate. These conflicts may arise due to habitat loss, competition for resources, and safety concerns, requiring innovative strategies to ensure coexistence [107].

9.1.4 Illegal logging and unsustainable practices

Illegal logging and unsustainable forestry practices contribute to deforestation, habitat degradation, and loss of biodiversity. Enforcing regulations, promoting

sustainable harvesting methods, and addressing the underlying drivers of illegal logging are ongoing challenges [28].

9.1.5 Fragmentation and loss of connectivity

Fragmentation of forest landscapes due to infrastructure development and land-use changes hinders wildlife movement and disrupts ecological connectivity. Maintaining or restoring connectivity is crucial for the long-term viability of species and ecological processes [70].

9.2 Future directions and research opportunities

9.2.1 Integration of technology

Advancements in technology, including remote sensing, GIS, and machine learning, offer new opportunities for monitoring and managing forest ecosystems. Integrating these technologies can enhance our ability to collect and analyze data, leading to more effective decision-making [108].

9.2.2 Genomic approaches in conservation biology

Genomic techniques provide insights into the genetic diversity, adaptation, and health of forest species. Applying genomics in conservation biology can inform strategies for preserving genetic diversity and enhancing the resilience of forest ecosystems [7].

9.2.3 Climate-smart forestry

Implementing climate-smart forestry practices involves considering climate change impacts and incorporating adaptive strategies. Research can focus on developing climate-resilient tree species, assessing the vulnerability of forests to climate change, and identifying effective adaptation measures [109].

9.2.4 Community-based conservation

Engaging local communities in forest conservation and management is crucial. Research can explore effective community-based conservation models, address socioeconomic factors influencing forest use, and enhance collaboration between communities and authorities [22].

9.2.5 Ecosystem services assessment

Evaluating and quantifying the ecosystem services provided by forests is essential for demonstrating their value to society. Future research can focus on developing standardized methods for assessing and valuing ecosystem services, providing a basis for informed decision-making [110].

As sustainable forest land management continues to face complex challenges, ongoing scientific research, and innovative approaches are crucial for developing effective solutions and ensuring the long-term health and resilience of forest ecosystems.

10. Conclusions

Sustainable forest land management is a multifaceted discipline that demands a holistic and scientifically rigorous approach. By integrating ecological principles, technological advancements, and community engagement, we can strive toward a future where forests continue to thrive, providing essential services for both nature and humanity.

Forest Lands Restoration aims to rejuvenate the supply of goods and services within forested areas. The feasibility of restoring the original forest ecosystem or pursuing a more attainable objective is determined by the ecological context. Economic considerations dictate the availability of resources and whether there's a need for direct financial returns to justify reforestation efforts. In some cases, rehabilitation rather than full restoration may be preferable [111].

Social factors, including land tenure patterns, legal frameworks, and community structures, play a crucial role in determining whether communities actively engage in the restoration process. Without community involvement, any form of Forest Landscape Restoration is unlikely to succeed. Strengthening restoration efforts involves integrating cross-disciplinary scientific knowledge to inform policy decisions and implementation. Additionally, considering stakeholder perspectives regarding ecosystem service choices is vital.

The success of forest land restoration activities can be furthered by implementing incentive schemes like payments for ecosystem services. However, more research and experimentation are necessary to explore alternative options, particularly in non-forest ecosystems. Successful restoration initiatives must address both forest land management aspects, such as sustainable food and timber production, and demand-side factors, including waste reduction and shifts in consumer behavior.

There are synergies between promoting restoration in international policies and biodiversity targets. Nevertheless, due to the extent and pace of environmental change, there are inherent limitations to restoration efforts. Therefore, successful restoration largely involves managing change, as achieving a return to pristine historical ecosystem states may be challenging or unattainable in certain areas.

Forest land degradation presents a widespread challenge to human societies, primarily influenced by socioeconomic factors. It compounds food insecurity, emits greenhouse gases and aerosols, contributes to biodiversity loss, and compromises various ecosystem services like clean drinking water access and air quality regulation. Climate change is anticipated to intensify degradation in many regions, while the associated emissions and reduced carbon sink capacity further exacerbate climate change. Land-based solutions focused solely on greenhouse gas mitigation, such as large-scale afforestation or bioenergy plantations, risk exacerbating forest land degradation and may yield unintended adverse societal and environmental impacts.

However, numerous studies indicate that degradation can be halted and reversed through appropriate forest land management practices, offering co-benefits for various sustainable development objectives. Overcoming existing barriers to their implementation, including financial incentives, restructuring of counterproductive subsidies, access to knowledge and technology, enforcement of environmental policies, and effective spatial planning, necessitates multilevel governance backed by interdisciplinary scientific insights into natural, economic, and societal factors. Implemented meticulously and monitored across sufficient areas in collaboration with local stakeholders, forest land restoration measures should constitute a cornerstone of any comprehensive strategy for global climate change mitigation and sustainable development.

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Section 2

Biodiversity Conservation

Chapter 3

Forest Resources Value Chain Analyses: Alternative Development Pathways toward Biodiversity Conservation and Sustainable Forest Management in Ghana

Mark Aferdi Dadebo, Gordon Kofi Sarfo-Adu, Stephen Omari and David Galley

Abstract

The value chain development of forest products and ecosystem services is important for sustainable forest management (SFM), especially in developing countries where the livelihoods of users and communities depend on timber and non-wood forest products (NWFPs). This chapter explains why and how NWFPs and ecotourism services value chain analyses need to be integrated into forest resource planning and management in Ghana. The chapter identified and analyzed all aspects of NWFPs and ecotourism services value chains and their roles in biodiversity conservation. The value chain analyses were approached through desk analysis of secondary information, field visits and interviews with key stakeholders. Theories on the concepts of value chain analyses and NWFPs and ecotourism services value chain analyses were provided. The study proposed alternative development pathways for NWFPs and ecotourism services value chain analyses and the institutiogramme for ecotourism services. It identified the link between these value chain analyses and the impact on forest biodiversity conservation. The study concludes that Ghana is faced with policy implementation challenges towards SFM that could be addressed by applying value chain analyses. This would help to increase policy understanding that there are alternatives to the current timber production, illegal farming and illegal mining practices on the forest landscape.

Keywords: value chain analyses, non-wood forest products, ecotourism services, forest biodiversity conservation, sustainable forest management, Ghana

1. Introduction

Forestry in Ghana is increasingly becoming complex due to the need to balance highly varied interests by increasing categories of stakeholders. A range of forest products and ecotourism services are recognized during planning when making

choices of sustainable management options. Ecotourism services are increasingly being viewed as a tool that can promote biodiversity and forest conservation in Ghana.

Ghana is one of the major producers and exporters of tropical timber products and continues to contribute to the domestic use and export of non-wood products. Ghanaians produce and market a diverse range of forest products and offer ecotourism services for the local, regional, and international markets. For decades, forestry has focused on the timber industry, and wood production practices have resulted in large-scale uncontrolled deforestation and forest degradation. Illegal farming and mining continue unabated. Deforestation and forest degradation have become serious environmental issues and are currently progressing resulting in the reduction of forest ecosystem productivity and biodiversity.

For the NWFPs and service sectors of the economy, due to increased competition, entrepreneurs and small and medium enterprises must find ways to stay competitive in the local, regional, and international markets. One of the ways to achieve competitive advantage while conserving the resource base is through forest products and services value chain analyses. Many studies have been conducted on the supply chain analyses of forest products [1–3]. However, in Ghana, little emphasis has been placed on the effect of analyzing the current and potential values of NWFPs and ecotourism services toward minimizing forest degradation and deforestation.

The objective of this chapter is to document the relationship between NWFPs and ecotourism services chain analyses and forest biodiversity conservation that enhance sustainable forest management in Ghana. It provides key considerations toward a better understanding of the manifold values of forest resources and identifies ways of incorporating these values into integrated forest planning and management.

The chapter provides a brief background of forest resources in Ghana, a theoretical examination of the concept of value chain analyses, NWFPs and ecotourism services value chain analyses, the models of value chain analyses that could be applied in Ghana, the challenges in these forestry subsectors, biodiversity conservation efforts, and the role of governance in NWFPs, and service management toward sustainable forest management. This can serve as useful information for the development of entrepreneurship in small- and medium-scale enterprises (SMEs) in Ghana's non-wood forest and ecotourism sectors. It can help in putting more premium on NWFPs and ecotourism services value chain analyses and its influence on integrated planning toward biodiversity conservation.

2. Methods

This chapter was prepared to identify and analyze all aspects of the NWFPs and ecotourism services value chains and their roles in biodiversity conservation in Ghana. The value chain analyses were approached through a desk study (secondary information collection on the subject matter), field visits, and interviews with key stakeholders in the Western, Eastern, Bono East, and Greater Accra Region of the country. The desk study was used to collect, review, and analyze all existing and relevant documents related to the wood and non-wood forestry sectors from all related institutions in Ghana.

Field visits were undertaken for the study, where the authors made efforts to collect data that was not available through desk research. This part included a collection of information through interview sections with all relevant stakeholders in the NWFPs and ecosystem services value chain. The key stakeholders included actors and services sectors' support of the existing business environment and interviews with representatives of the Ministry of Lands and Natural Resources, Forestry Commission, Ministry of Trade and Industry, and selected MMDAs in the regions mentioned supra.

Agents of selected SMEs that are working with the NWFPs sector in these regions were purposively selected and interviewed. Information related to their operations was collected through the interview process. Efforts were made to analyze the indirect value chain participants such as logistics and marketing aspects of business operations. Finally, the producing, processing and marketing aspect of the NWFPs ecotourism services value chain was covered through interviews with all relevant actors in the targeted regions.

Focus groups were organized with participants from key sector stakeholders from all points of the value chain. The primary goal of the focus group sessions was to elaborate and discuss the main findings of the research. The recommendations and proposed policy interventions were complemented by the sector stakeholders, resulting in this paper, which reflects the needed strategies and identifies the gaps in the non-wood forest products (NWFPs) and ecosystem services sectors of Ghana.

3. Forest resources of Ghana

The 2012 Ghana Forest and Wildlife Policy and other subsequent publications provide baseline information on the forest resources of Ghana [4]. The total area of Ghana is about 23.9 million ha. As of 2021, the Forestry Commission indicated that high forest vegetation zones (wet evergreen, moist evergreen, upland evergreen moist semi-deciduous, dry semi-deciduous, southern marginal, and southeast outlier forests) covered 8.2 million ha. The high forest zone covers seven vegetation zones with distinct associations of plant species and corresponding rainfall and soil conditions. The savannah zone that is made up of the Guinea savanna and Sudan savanna covers 15.7 million ha.

According to the Food and Agriculture Organization (FAO), in 2020, Ghana's forest cover was close to 7.99 million ha, accounting to 33% of the total land area. The country's forest has also been classified into open forest, closed forest, and plantation forest. The forest resources have been categorized into different use types, namely, the reserved and unreserved forest areas based on management objectives. The forest reserve covers about 24.2% of the total land area [5]. Currently, there are 282 gazetted forest and wildlife reserves (protected areas) covering 22.754 million ha of which 216 (covering 1.6 million ha) are in the high forest zone and 66 are located in the savannah zone [6]. Both forest and wildlife reserves cover about 16.2% of the total land surface area (**Figure 1**). The reserved areas account for 1.77 million ha of forestland, of which 1.634 million ha are under the management and control of the Forest Services Division, while the Wildlife Division manages 0.136 million ha [7]. Areas for the conservation of forest and wildlife constitute about 16.2% of the total land area of Ghana [4]. Among the two types of forest reserves, that is, production (80%) and conservation areas (20%), the production of timber is mainly concentrated

in the southwestern part of Ghana where forest types range from wet evergreen to semi-deciduous.

Ghana was once well-endowed with forest resources, and the forest offers many timber and non-timber goods and services for the rapidly growing economy. The forests provide many products for the local and international economy, which the local population subsists [5]. However, these resources are depleting faster due to a variety of factors including agricultural expansion and overexploitation of forest resources. In addition to the natural forest areas, there are stands of trees, including plantations established by the government and private and industry investors, and community-based forests or plantations made by farmers. The forest resources of the country play a significant role in income generation and food provision for households with forest products providing sustenance and revenue. Forest fringe communities depend on the forest resources through the collection and production of non-wood products such as fuelwood, hunting for game, collection of snails and mushrooms, gathering of medicinal herbs and chewing sticks, and both legal and illicit logging [8].

Though the diversity of forest resources in Ghana is remarkable, the status of deterioration of these resources continues to be monitored. The primary causes of serious threats include loss of forest cover due to shifting cultivation, illegal felling, conversion of forest lands for urban expansion, and other biotic pressures. Illegitimate cutting of trees has impacted the climatic conditions at a micro level. It has affected the soil quality, hydrological cycle, and biodiversity of the country, thus making the country more exposed to natural calamities and climate change. Most forests are under threat due to strong anthropogenic pressure, extensively due to collection of fuelwood and livestock grazing. Effective management strategies that take into account restoration and also promote judicious use of forest resources would ensure sustainability in the long run.

Ghana's forest resources are being lost at an alarming rate over the years. One-third of Ghana's total land area of 23.9 million hectares was occupied by tropical natural forests at the beginning of the twentieth century [9]. The World Bank Group provided the status of Ghana's forest resources [10]. The Global Forest Resources Assessment 2020 indicated that Ghana lost an average of 135,000 hectares of natural forest per year between 1990 and 2000 at a deforestation rate of 1.7% per annum and a further 115,000 hectares between 2000 and 2005 amounting to about 26.0% of forest cover loss between 1990 and 2005 [11]. Currently, Ghana is experiencing a 2% rate of annual deforestation and forest degradation, which translates into approximately 135,000 ha/year of forest cover loss due to anthropogenic causes [12]. In 2021, Ghana had a forest area of nearly 80,000 km^2. This represented roughly 35% of the country's total land area. In contrast, between 2008 and 2015, the forest stretch followed a contracting trend. In 2021, around 10,400 ha of primary forests were lost in the country, which was the highest area of forest lost since 2001. The primary cause of tree cover loss in Ghana is shifting agriculture, which usually emanates from small- and medium-scale agricultural activities. In 2019, over 80,000 ha of tree cover was lost through shifting agriculture.

4. State of Ghana's forests for biodiversity conservation

Forest biodiversity encompasses the variety and variability of life forms within forest ecosystems, including flora, fauna, and microorganisms, as well as the genetic diversity within these species [13]. The rapid expansion of sustainable forest

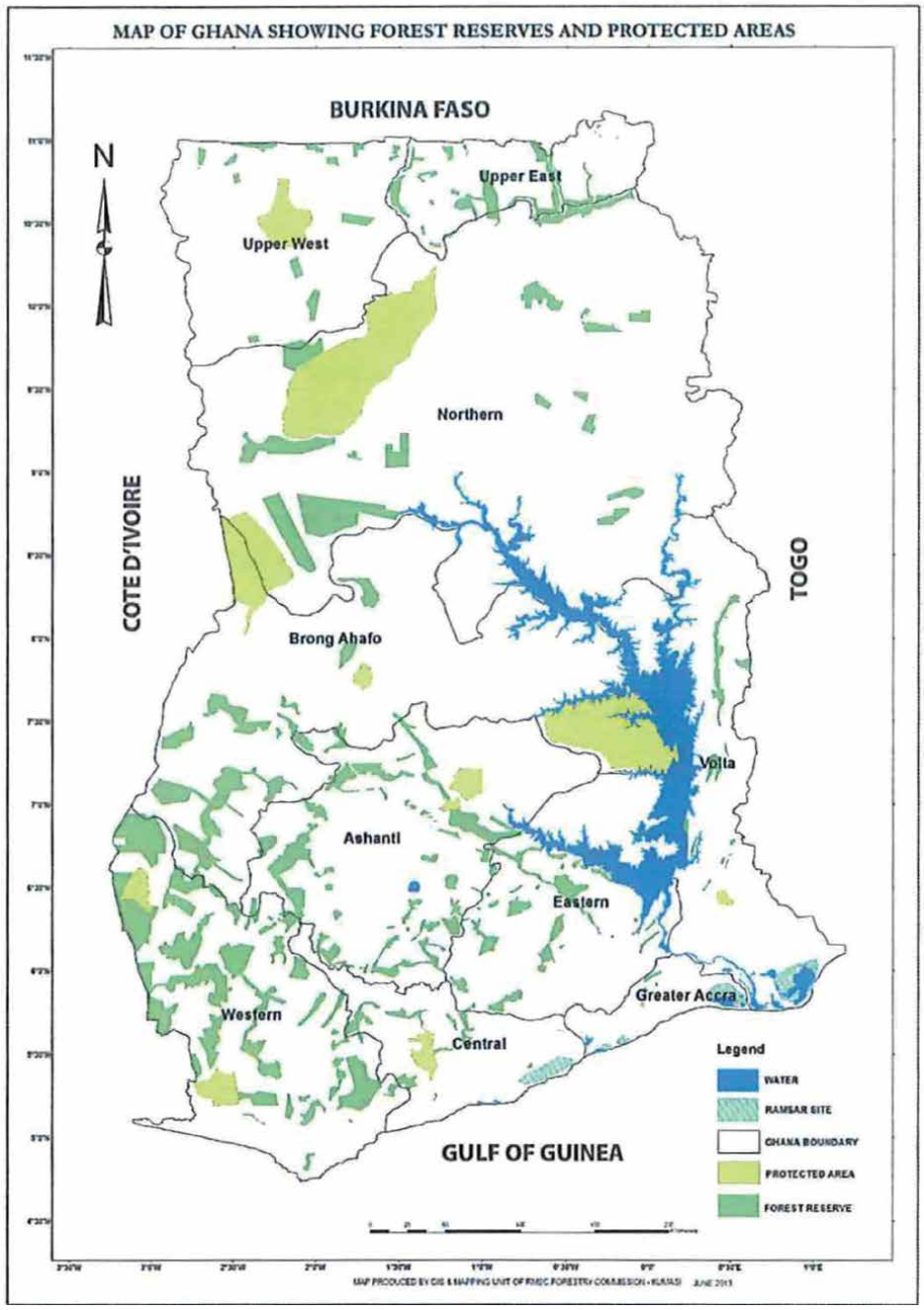


Figure 1.
Map of Ghana showing forest and wildlife reserves. Source: Ministry of Lands and Natural Resources, Ghana's 2012 Forest and Wildlife Policy.

management has led to the adoption of various forest management frameworks intended to safeguard biodiversity [14]. However, it is essential to consider the impact of forest management practices on biodiversity, as the reduction of dead wood due

to harvesting and sanitation fellings can negatively affect the biodiversity of forest ecosystems [15].

Ghana is rich in biodiversity. There are over 3600 plant species. Forty-three species are endemic. The fauna of the terrestrial ecosystem comprises a diverse array of species including several of conservation concern. Records show that there could be as many as 221 species of amphibians and reptiles, 724 species of birds, and 225 mammalian species (with 93 recorded to inhabit the savanna ecological zone). The faunal diversity includes 225 mammal species, 74 bat species, 37 rodents, 724 birds, 221 amphibians and reptiles, and 850 species of butterflies in the forest zone alone [16–18]. The wet evergreen forest is floristically the most rich, while the drier southern marginal forest is species-poor. The moist evergreen and moist semi-deciduous forest zones are the most important for commercial timber species.

In managerial terms, this means conserving biodiversity by creating parks and reserves with minimal to hardly any human influence. Some species need to be protected because of their restricted distribution or their habitat degradation or destruction. However, the forest biodiversity of Ghana faces significant threats from deforestation and forest degradation driven by factors such as overexploitation of NWFPs by local communities [16, 19]. These activities have led to a sharp decline in forest biodiversity and ecosystem services. Additionally, the impact of cocoa farming on vegetation has resulted in the establishment of farms in clear-cut forests, providing poor habitats for a wide range of biodiversity [17]. Furthermore, the study highlighted the importance of recognizing certain areas in Ghana as Key Biodiversity Areas, emphasizing the significance of specific regions for biodiversity conservation [18].

The management of Ghana's forests and biodiversity conservation has seen the introduction of new dimensions, such as the planting and maintenance of indigenous timber and non-timber tree species, as well as the involvement of local farmers in the rehabilitation of degraded tropical forests [20]. Moreover, the involvement of local communities in conservation efforts, such as the use of livelihood support activities, has been identified as a strategy to achieve conservation objectives in Ghana [21]. Additionally, traditional biodiversity conservation strategies, including sacred forests, taboos, and totems associated with various animal species, have been evaluated for their effectiveness in biodiversity conservation in Ghana [22].

The biodiversity of Ghana's forests faces significant challenges from deforestation, overexploitation of forest products, and the expansion of agricultural activities. Efforts to address these challenges include the involvement of local communities, the implementation of new forest management dimensions, and the evaluation of traditional conservation strategies. These findings underscore the importance of sustainable forest management practices and conservation efforts to preserve Ghana's forest biodiversity. The Protected Areas strategically located in the country are an essential element of any strategy to conserve tropical forest biodiversity (**Figure 1**).

5. Some challenges to sustainable forest management in Ghana

Forest resources are critical for the conservation of biological diversity and water and soil resources as well as for meeting our needs for wood and non-wood forest products. The concept of sustainable forest management has different meanings but involves perpetuating ecological, economic, and/or social forest assets [23]. The Food and Agriculture Organization (FAO) describes sustainable forest management

(SFM) as a strategy for securing an improved livelihood for present generations while maintaining the potential of the forest heritage for future generations [23]. The FAO noted that SFM involves planning the production of wood for commercial purposes as well as meeting local needs for fuelwood, poles, food, fodder, and other purposes. It includes that the protection or setting aside of areas to be managed as plant or wildlife reserves or for recreational or environmental purposes is imperative. The concept therefore incorporates human preferences for timber and non-timber products; preferences for marketed as well as non-marketed products and services; the preferences of industrial as well nonindustrial agents, including local people; and the preferences of present as well as future generations [24].

Policies and practices of sustainable forestry and SFM in Ghana have a long history of achievements and challenges. Adoption and implementation of sustainable forestry practices are essential for sustaining forest resources; however, the development of effective policies and strategies to achieve them is problematic [25]. The authors studied the limited understanding of the interaction between obtrusive forest policies and indigenous tenure systems and how this affects SFM in Ghana, as current statutes provide few incentives for farmers to engage in sustainable practices. According to [26], the characteristics of small and medium forest (SME) enterprises have an impact on SFM in Ghana. This study advocated that forest policies must promote sustainable management of forest resources by enforcing registration and permit laws. SMF enterprises must be consistently monitored and supervised to ensure that their activities are guided by policy and their compliance is rewarded through capacity building and government support.

The Voluntary Partnership Agreement (VPA) between Ghana and the European Union (EU) was ratified to speed up the good governance process in the forestry sector of Ghana to promote sustainable management of forest resources and enhance and sustain the trade relationship with the EU [27]. The study observed some challenges that affect the full realization of the expected benefits associated with VPA. The study recommended the use of stakeholder consultations and workshops to help address the interagency coordination problem, which will help optimize the enforcement of the VPA.

Another challenge to SMF in Ghana is that there is inadequate information and guidelines that help decision-makers understand the economic value of the forests to local communities as these values influence how they respond and support policies and interventions [28]. This study indicates that local communities around reserves are likely to support forest management initiatives that promote sustainable use of the forest resources in the reserve.

Tindan delved into the causes and impact of deforestation on local-level sustainable forest management in Ghana by examining the causes and impact of deforestation and investigating the conditions for local-level sustainable forest management in Ghana [29]. A key argument advanced by this study is that sustainable forest management is a collaborative activity; hence, at the local level, efforts should be made to ensure broad public participation of all stakeholders in decision-making and policy design and implementation.

The perception of local forest fringe communities impacts the SFM agenda and practices. This study examined stakeholders' perceptions of forests and their implications for sustainable forest management in Ghana [30]. The study discovered that the call for sustainable management of natural resources, particularly in the forestry sector, is highly needed in Ghana. The research findings confirmed that stakeholders' participation in SFM in both communities has been met with a myriad of challenges

that are deeply rooted in the stakeholders' perceptions of what constitutes forest and the classification of forest, which are present in the communities. The conditions for ineffective SFM in these communities have been determined by three factors: "access to," "nature of," and "right to" forest resources.

6. Theoretical framework

6.1 Value chain analyses and mapping

A value chain is a concept that describes the series of interrelated activities within a business that add value to the product, starting with raw materials till the conversion into a valuable product or service to market. The value chain therefore focuses on the market collaborating strategy, emphasizing the connections between production, marketing, and so on activities of the products and services effectively and efficiently [31]. Breaking down practices of business entities into value chain activities enables a more focused analysis of each activity regarding its value creation for customers [32]. Value chains can be mapped and analyzed using value chain analyses, which can include qualitative and/or quantitative tools [33].

Value chain analysis is a tool used to identify what consumers value and will pay for in a product or service (i.e., its value attributes) and where that value is created or destroyed in the chain. A value chain analysis is a strategic tool to analyze each of the activities in a business's value chain to increase the efficiency of the chain and gain a competitive advantage. This analysis requires the "mapping of the market" to track and analyze the contribution of the different chain actors and the relationships among themselves. An understanding of the interactions within a value chain helps identify the factors that influence how well or how badly the chain works [34]. Value chain mapping means drawing a visual representation of the value chain system. Maps identify business operations (functions), chain operators and their linkages, as well as the chain supporters within the value chain.

The resulting market map defines the value chain actors, the enabling environment and the critical service providers. The enabling environment includes critical factors that create the operating conditions within which the value chain operates, such as infrastructure, policies, and regulations, as well as institutions and processes that shape the market ecosystem [35]. According to [36], these factors are beyond the control of the value chain actors, but understanding them is critical to ascertain the trends affecting the chain and the drivers of these trends, thereby identifying opportunities for lobbying. Service providers may include business services that provide support to the value chain, such as providers of market information, financial services, transport services, research and development, and extension education services.

6.2 Non-wood forest products value chain analyses

Economic analyses of the value chain are aimed at measuring and interpreting the profitability and sustainability of the value chain operations for all the actors directly involved. They also analyze the profitability and marketing margins obtained by actors at various nodes of a product's value chain [33]. NWFPs have been analyzed in several studies for their economic benefits and value chain. These products have economic value and play a significant role in supporting rural livelihoods and the

bioeconomy [37–39]. In most tropical forest countries, forest fringe communities, including farmers, depend on income from collecting, processing, and marketing forest products. A conclusion by [33] is that increasing cash income to local communities while simultaneously creating incentives for the conservation of trees and forested ecosystems is a win-win situation. The ability of these farmers to earn and maximize income from trading forest products depends on the economic factors relating to the products collected. The incomes derived from these activities depend on the availability of inputs, such as processing materials, labor, and transportation.

In the concept of forest resources sustainability and sustainable development of the forestry sector, NWFPs have great importance, in particular, the economic, environmental, and social effects of the NWFPs [40]. Many countries are making strategic efforts to move from wood-based production systems to non-wood production systems to reduce the negative impacts of deforestation and forest degradation. NWFPs include goods of biological origin other than wood, derived from forests, other wooded land, and trees outside forests [41].

The commercialization of NWFPs has been one of the strategies for addressing rural poverty and forest degradation [42]. These products contribute to the livelihood of communities in both rural and urban areas and are economically important at national and global levels [43]. In forest communities, this strategy is demonstrated by marketing NWFPs as an opportunity for both livelihood improvement and forest conservation.

The NWFP value chain development is important for sustainable forest management, especially in tropical developing countries where the livelihoods of several people directly depend on timber and non-timber forest products [44]. Value chain development and support should focus on products that have local, regional, or international markets. To capture all key actors in the non-wood value chain, it is important to understand the following: (1) the types of NWFPs used and preferred at household level, (2) the types and quantities of NWFPs marketed, (3) the value addition done along the chain, (4) the income generated from NWFP trade, and (5) the influence of local deforestation and forest degradation status on any of these.

In the view of [45], value chain analyses can be used to explain and help in the understanding of the commercialization of NWFPs by focusing on the whole range of the activities and transfers involved in the production, transport, distribution, and promotion of particular commodities. NWFPs have significant importance in the value chain analyses. They contribute to the livelihoods, income, and trading of households and communities in both rural and urban areas worldwide [39]; offer a wide range of products and services that benefit human well-being; and play a crucial role in provisioning forest ecosystem services.

The value chain analyses of NWFPs help in understanding the map of the value chain, the value added by households, and the impact on household income. They also highlight the potential of NWFPs for diversifying the forest bioeconomy and strengthening the economic viability of rural areas [46]. The success of NWFP value chains depends on strong relationships among market actors, creative problem-solving, and adapting strategies to meet the changing needs of local partners [47]. Proper policy formulation and commercialization of NWFPs through value chains are essential for sustainable livelihoods and the economic potential of communities relying on NWFPs. Forest owners play a key role in the value production of NWFPs and can benefit from the opportunities offered by service-based forest value production.

7. Alternative development pathways for non-wood forest products value chain for Ghana

NWFPs in Ghana includes all products gathered from forests whether for commercial or subsistence purposes [48] and include those for household use and trade. As pressure increases on forest resources, a clear picture of their products and services, users, and uses is needed for policy-making and forest management planning. The study was done to identify strategies of incorporating NWFPs in forest management planning by examining the demand for them and assessing their supply.

The values of non-wood forest products derived from sustainably managed forest ecosystems have been provided [49]. These values have been categorized under forest products and services, and for each of these products and services, their values have been explained.

NWFPs value chain analyses in Ghana should focus on a holistic view of value chains in their different dimensions: functional, economic, social, and environmental [50]. They should encompass and integrate a large number of concerns driving the impact and performance of value chains.

Alternative pathways for NWFPs value chain for Ghana can be developed by focusing on diversification, stakeholder involvement, and sustainable governance. Diversification of the forest bioeconomy to include NWFPs can provide additional income and strengthen the economic viability of rural areas [51]. Stakeholder interaction and expert involvement can help identify the future potential of NWFPs and their value networks, enabling forest owners to focus on the joint production of wood and non-wood resources [52]. Additionally, [53] indicated that integrating NWFPs into the bioeconomy requires strengthening formal markets, developing value-added products, and embedding sustainable governance into the development of the NWFP industry. This can be achieved through legislative, economic, and information-based measures, which can support the supply chain and promote the market and bioeconomy potential of NWFPs [26]. Overall, a combination of diversification, stakeholder involvement, and sustainable governance can help develop alternative pathways for the value chain of NWFPs.

Access to non-wood forest products in Ghana provides great benefits to forest fringe communities; however, the utilization of the benefits as either commercial commodities or personal goods can determine the intensity of collection of these products from the forest, which can lead to either potential degradation or continued regeneration of forests. These could come under the traditional practice or commercializing the traditional livelihoods.

Studies have dealt with alternative development pathways for NWFPs that hinge on sustainable development principles, for example, [54–56]. The alternative development pathways can be created to analyze non-wood forest product value chains that are socially, economically, and environmentally sustainable in Ghana. The International Labour Organization [57] provided three pathways that Ghana should consider:

1. *Social analyses*: proposes a profile of the value chain based on impact and risks in the following fields: working conditions, forest resources rights and access to non-wood products, gender equality, food and nutritional security, social capital, and living conditions.

2. *Economic analyses of value chains*: financial indicators, calculation of added value, measurement of competitiveness, distribution of income, and so forth;

3. *Life cycle assessment*: focusing "damage" on resource depletion, ecosystem quality and human health, impact on climate change, and monitoring of biodiversity.

The alternative NWFP value chain for Ghana should be broken down into several subsets of activities: production, collection, processing, storage, transport, marketing, and sale (**Figure 2**). According to [58], the relative importance of each of these activities differs from product to product; they may not occur sequentially, and some may even be repeated or omitted for particular products.

An alternative NWFP marketing value chain for Ghana as shown in **Figure 3** should include the following key activities of collections, cultivation, storage, processing and transportation.

7.1 Potential distribution channels for NWFPs in Ghana

Marketing of the NWFPs is the process of exploring which products potential customers will purchase and then producing, processing, promoting, and distributing the products at a profit [59]. In most instances, collectors of NWFPs do not market their products; rather they sell the products to a customer (the middleman). If the goal is for the communities to retain a larger portion of the income generated by NWFPs, the task of both the producer and those involved in assisting the market development of NWFPs is to transform the current process from selling to marketing at the community level. Marketing strategies for successful NWFP commercialization are important, especially in those rural economies where NWFPs represent a considerable source of income for small- and medium-scale forest-based enterprises [60].

Product distribution channels for NWFPs should involve various factors such as the involvement of intermediaries, the influence of channel members on key decisions, and the impact of conflicts on channel relationships. In Ghana, different NWFP distribution channels are proposed:

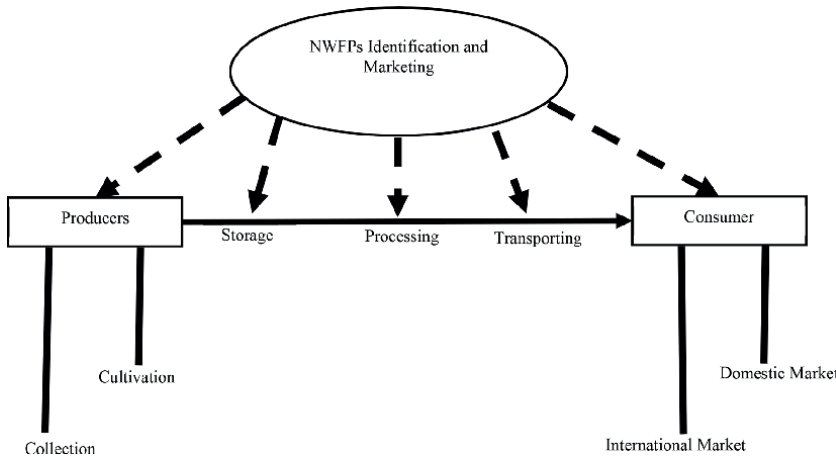


Figure 2.
Key activities in NWFP value chain.

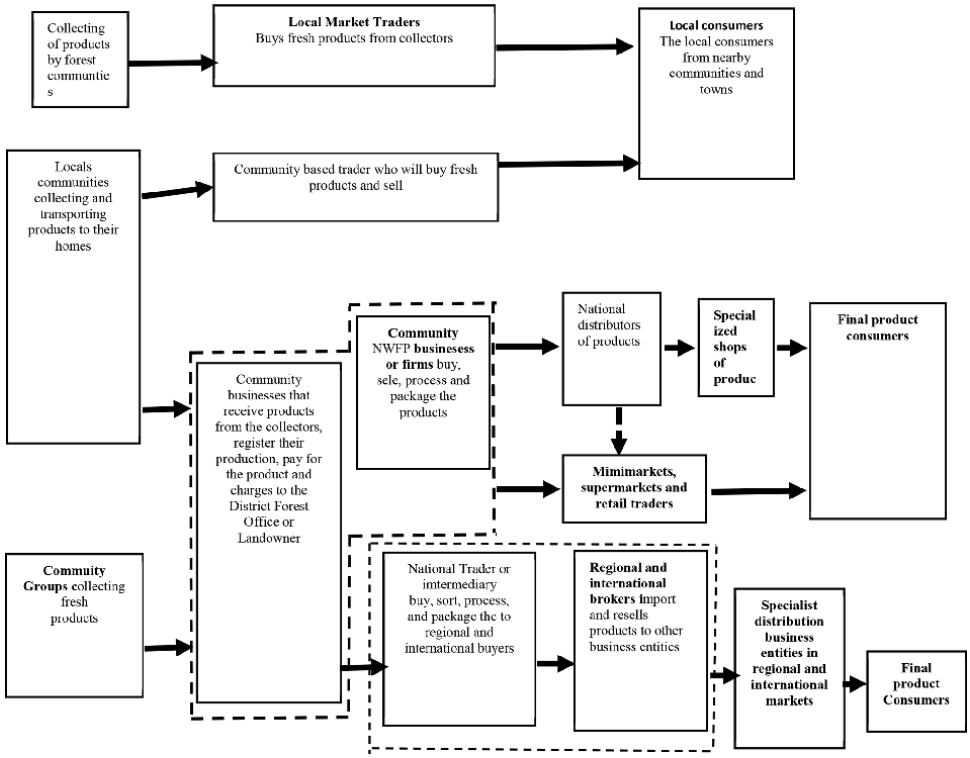


Figure 3.
An alternative value chain map for NWFPs for Ghana adapted from [59].

1. *Government-Managed Forest: Distribution channel 1*: Forestry Commission District Offices—Harvesters/Collectors—Processors—Wholesalers—Retailers—Consumers.

2. *Government-Managed Forest: Distribution channel 2*: Forestry Commission District Offices—Harvesters/Collectors—Agents/Traders (Intermediary Contractors)—Processors—Exporters.

3. *Government-Managed Forest: Distribution channel 3*: Forest Commission District Offices—Harvesters/Collector—Processors—Wholesalers (In Processing)—Retailers—Consumers.

4. *Government-Managed Forest: Distribution channel 4*: Forest Commission District Offices—Harvesters/Collectors—Processors (in Processing or Export)—Exporters—Consumers.

5. *Community-Managed Forest: Distribution channel 6*: Harvesters/Collectors from Off Forest Reserve Protected Areas—Wholesalers—Processors—Retailers.

6. *Community-Managed Forest: Distribution channel 5*: Harvesters/Collectors from Off Forest Reserve Protected Areas—Wholesalers—Primary Processors—Exporters—Importers—Secondary Processors—Consumers.

Based on the six distributional channels proposed for Ghana, each actor in the mapping will create different value additions for NWFP as follows:

- *Forestry commission (FC) district office*: The FC District Offices are the agents that play a production role, creating the first added value for NWFPs in the value chain. The added value the FC creates in market channels is not economically high. The added value of the FC should be highest when it directly sells NWFPs to the processors for export purposes (distribution channel 4). The added value created could be the highest, but the product requirements for the key NWFPs could be highest.

- *NWFP collectors from forest reserves managed by FC*: These are actors who obtain entry permits from the District Forestry Office to enter and collect the NWFPs. They are collectors who should appear on channel 1 and channel 2. The added value that these actors receive will not be much, so in addition to fresh product collection, they also will participate in other labor activities such as product collection as a secondary source of their income.

- *NWFP collectors from off-forest reserve areas*: These are actors that collect NWFPs from lands outside of government-managed protected areas. They are collectors who should appear on channel 1 and channel 2. The added value that these actors receive will not be much, so in addition to fresh product collection, they also will participate in other labor activities such as product collection as a secondary source of their income.

- *NWFP processors*: The processing actor is an agent contributing to the added value of NWFP through processing and exporting activities. At the same time, the agent should be present in the product distribution channels. If the processors buy the products directly from the FC, they would receive a higher added value.

- *NWFP wholesalers*: Being a commercial agent, wholesalers play an important role in the distribution of NWFP to the domestic markets. The wholesalers should transport the products for sale to retailers within the production districts and can also ship the products outside of Ghana.

- *NWFP retailer*: In the domestic market, the retailer is the agent that should bring NWFPs to consumers.

Based on the distribution channels proposed, Ghana should adopt the value chain map for NWFPs as shown in **Figures 4** and **5**.

8. Ecotourism value chain analyses

Ecotourism can be summarized as conservation and nature-based, containing educational and interpretation features to build local and tourist awareness while minimizing the negative impact on the natural and sociocultural environment and generating economic benefits for host communities [62, 63]. Ecotourism is conceived as a nonconsumptive, market-based approach to forest utilization that has received primary attention due to its potential economic and environmental benefits. It is composed of various

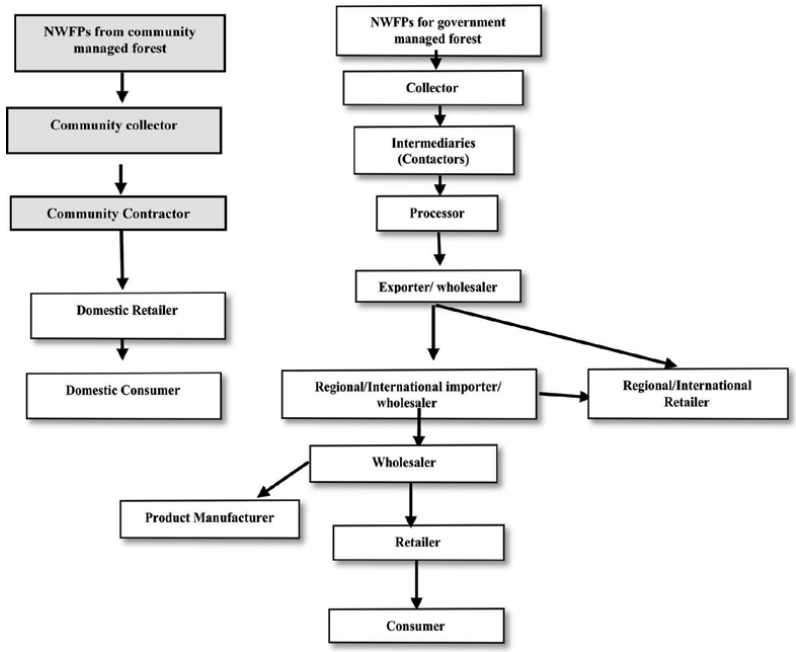


Figure 4.
Potential value chain map for NWFPs for Ghana adapted from Ref. [14].

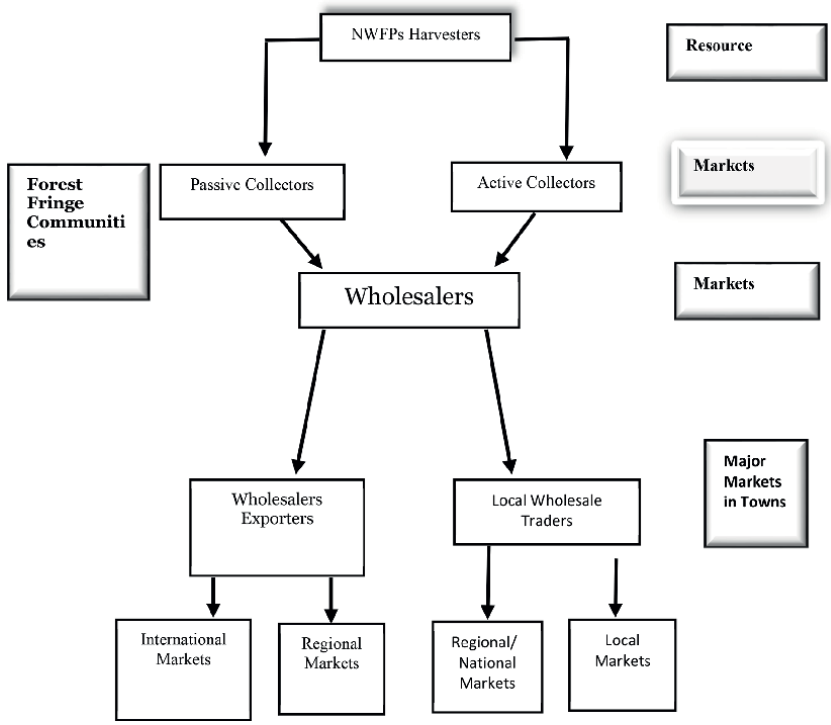


Figure 5.
Potential value chain map for non-wood forest products for Ghana adapted from Maisharou and Larwanou [61].

stakeholders, with the majority of them being small to medium enterprises that operate in different industries such as lodging, transportation, attractions, food and beverages, retail, and so forth [64] and therefore have complex value chains.

Ecotourism is emerging as an alternative development path that can enhance environmental conservation and promote sustainable livelihoods in many developing countries [65]. According to [66], the development of alternative forms of tourism, such as ecotourism, cultural tourism, and creative tourism, supports a different philosophy of tourism that integrates local populations and natural and human environments. Sustainable tourism has the potential to contribute to the United Nations Sustainable Development Goals at the local level [67]. Ecotourism, as a sub-component of sustainable tourism, involves visiting natural areas in an environmentally friendly manner and can provide direct benefits to local communities [68]. In the view of [69], ecotourism tourism value-chain can be an alternative pathway for socioeconomic development, as demonstrated in the case of Rwanda.

A typical ecotourism value chain was provided by [70]. The key ecotourism activities are: (i) product design and development, (ii) promotion and distribution, (iii) inbound transportation, (iv) accommodation and catering, (v) excursion, and (vi) outbound transportation (**Figure 6**). The study summarized the key actors to include: (i) consumers, (ii) suppliers, and (iii) related and supporting institutions.

8.1 Alternative development pathways for ecotourism value chain for Ghana

Ecotourism is an opportunity to provide for biodiversity maintenance and improvement, employment, visitor appreciation and awareness, cultural exchange, environmental education, revenue generation, and justifying protected areas. In the context of ecotourism, the value chain describes a full range of activities and the

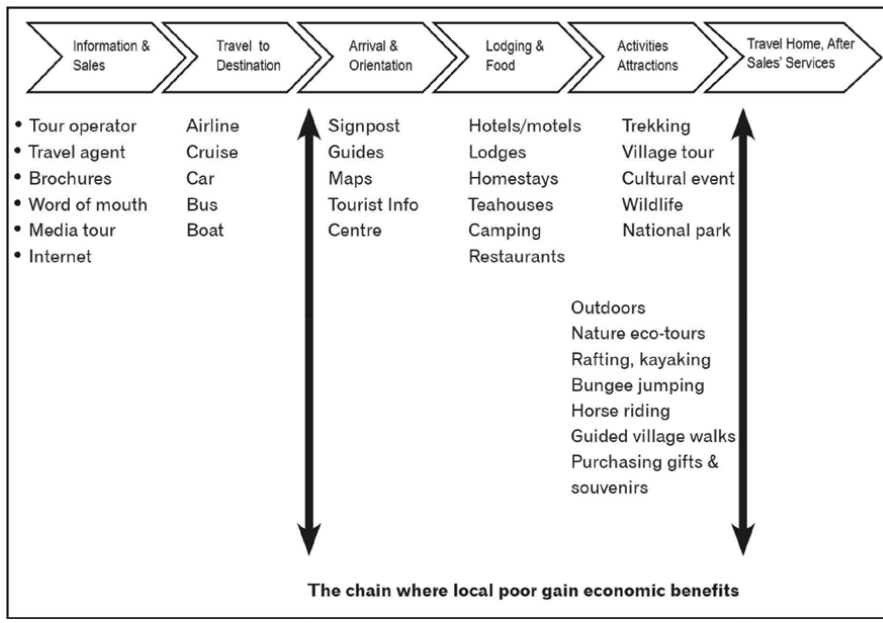


Figure 6.
Value chain in the tourism sector (source: Kruk et al. [32]).

different actors involved that are required to bring a nature-based tourism product or service from conception, through the different phases of production (involving a combination of physical transformation and inputs from various tourism producers), to delivery to the final consumers (tourists). The concept is increasingly being applied

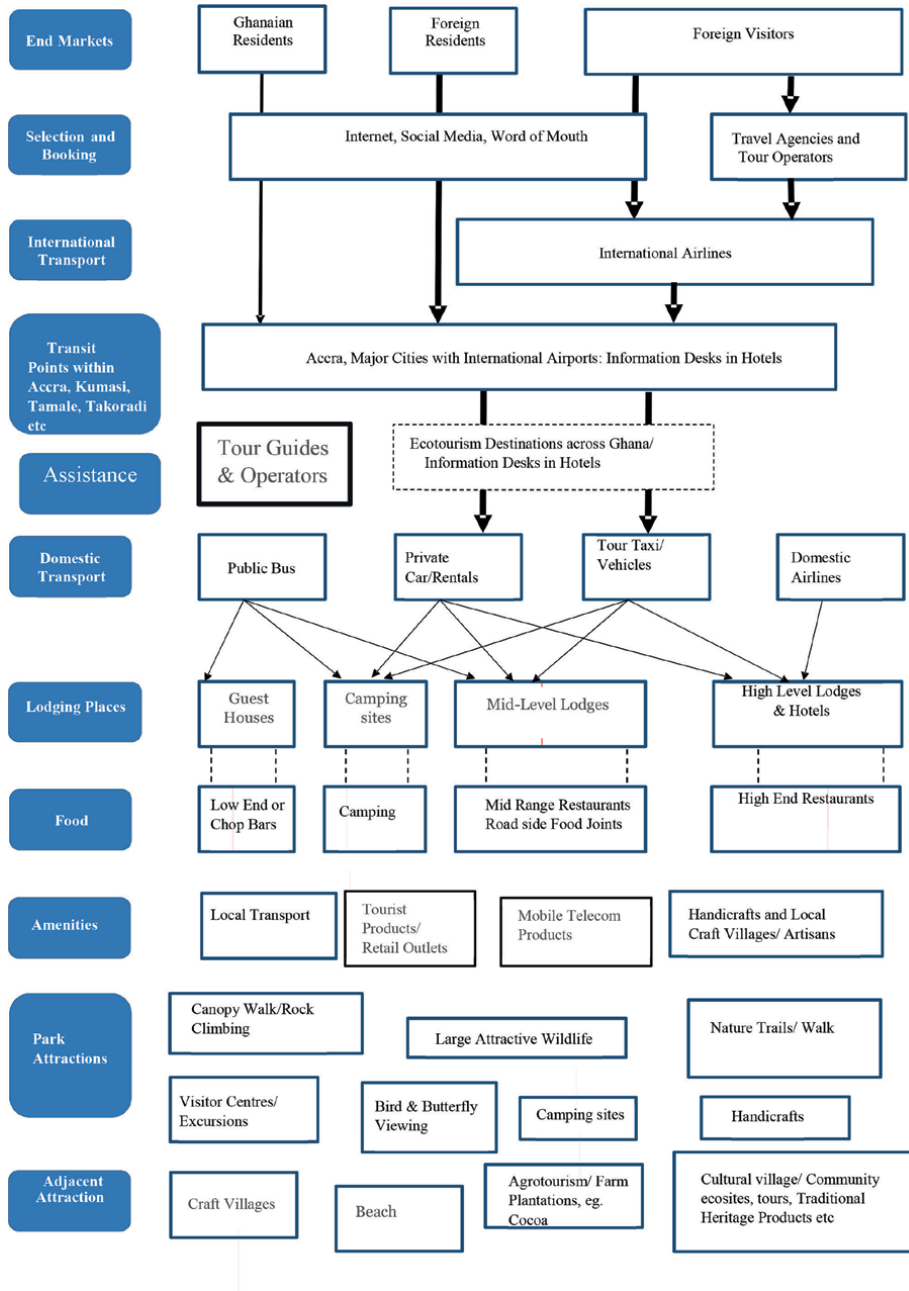


Figure 7.
Alternative development pathways for ecotourism value chain for Ghana adapted from United States Agency for International Development [72].

in the ecotourism context as a tool for business development [71]. According to [71], value chain promotion can bring the different ecotourism actors and institutions in Ghana at the micro, meso, and macro levels onto a common platform to improve the ecotourism sub-sectors competitiveness, reduce costs, and assure quality ecotourism products and services for visitors.

Figure 7 is an adopted ecotourism value chain that could be applied in Ghana for a sustainable visitor experience.

The delivery of a mix of ecotourism products and services to customers mobilizes different tourism actors, each specializing at different levels in the chain [71]. This nature-based tourism industry synchronizes interactions in local value chains to create an extended value chain, sometimes even global in scope. This larger interconnected system of value chains has been termed a "value system." The ecotourism value system includes the value chains of a tourism enterprise's supplier, the tourism enterprise itself, the tourism enterprise's distribution channels, and the final tourism enterprise's buyers (ecotourists).

9. Institutiogramme for ecotourism value chain for Ghana

The role of ecotourism sector of Ghana cannot thrive sustainably without a well-structured institutiogramme. An institutiogramme, according to [71], is a visualization of the relationship between people and institutions active in the ecotourism sector and field of analysis. The institutiogramme helps to analyze the environment and, specifically, the relationship between actors in the sector of the economy. It helps in identifying relationships to improve, to reconsider, or to be established to ensure a productive, viable, and sustainable ecotourism sector of Ghana. Furthermore, it assists in determining the position of NWFPs and ecotourism projects in the existing institutional setting.

The institutiogramme in Ghana is a useful tool to show the position of the NWFPs and ecotourism organizations and institutions in their environment and for discussing the relationships between ecotourism organizations in a network and determining their appropriateness for the effective and efficient achievement of the desired strategic goals and objectives. The institutiogramme therefore helps as a first assessment of the interests and involvement of ecotourism stakeholders in terms of their institutional relationships, coordination, and cooperation. Based on the proposed alternative development pathways for ecotourism value chain conceptualized for Ghana, an institutiogramme for Ghana that will support an integrated planning and management of the ecotourism sector of the economy would emerge (**Figure 8**).

10. Challenges in the forest resources value chain in Ghana

The policy and development of the forest resources value chain has been met with challenges, which when critically addressed could lead to stakeholders' attention to the protection and conservation of Ghana's forest estates. The key challenges faced in the NWFPs and ecotourism value chain include:

i. Deforestation and illegal logging with the attendant impact on biodiversity status with the socioeconomic and cultural implications.

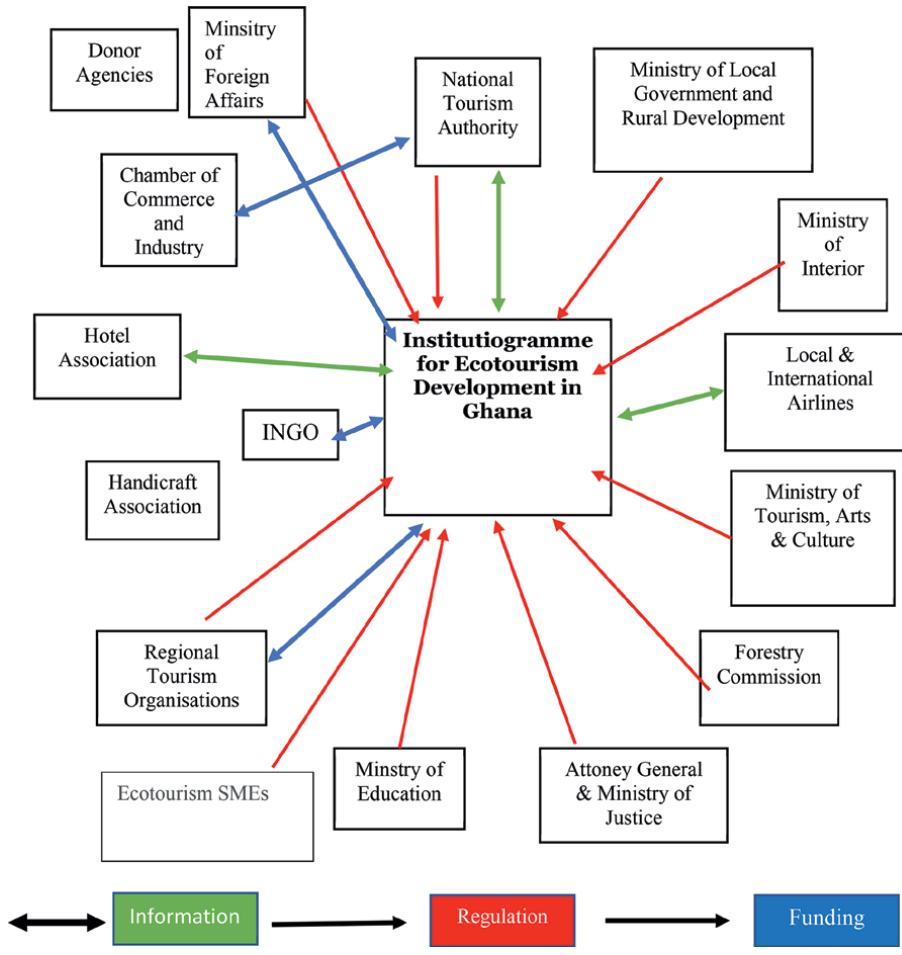


Figure 8.
Institutiogramme for ecotourism development in Ghana.

ii. The ucn-wood forest products that threatens plant and animal species found in their natural habitats.

iii. Inadequate appreciation of indigenous knowledge and practices in protecting and managing forest resources and current and potential values held by Ghanaians.

iv. Ecotourism concerns that are linked to environmental impact as well imbalance between tourism and conservation goals.

v. Low linkage between the NWFP and ecotourism industries and other sectors of the Ghana's economy.

vi. Quality of basic infrastructure required by visitors are minimal and often below acceptation to even down-to-earth ecotourists.

vii. Limited coordination among different influential stakeholders/actors in ecotourism context.

viii. Minimal integration of NWFPs and ecotourism development into Ghana's development.

ix. Sudden increase in demand for diversifying ecotourism experiences and corresponding proliferation of ecotourism sites with limited quality of services and underqualified products.

11. Conclusion and recommendation of the study

The study concludes that Ghana is faced with policy implementation challenges toward sustainable forest management. Some of these challenges could be addressed by applying key concepts of value chain, value chain analyses and mapping, the economic analyses of non-wood forest products value chain, and non-wood forest products value chain analyses. These analyses should provide the foundation to develop alternative development pathways for non-wood forest products and ecotourism value chains for Ghana. Also, the institutiogramme for the ecotourism value chain for Ghana should be strategically structured to address the many challenges in the forest resources value chain development toward sustainable development.

It is therefore recommended that the Forestry Commission (FC) of Ghana should identify the link and knowledge between NWFPs and ecotourism value chain analyses and the impact on forest biodiversity conservation. The Commission should collaborate with the academia and research institutions to study the proposed alternative NWFPs and ecotourism services value chain development pathways that would bring benefits to investors as well as foster integrated planning that considers sustainable forest resources management. This would help increase the understanding that there are alternatives to the current unsustainable timber production practices, unchecked illegal farming, and uncontrolled illegal mining on the forest landscape. The FC should adopt and enhance the institutiogramme in Ghana as a useful tool to show the position of the NWFPs and ecotourism organizations and institutions in their environment. This should open the relationships between ecotourism organizations in a network for discussion and determine their appropriateness for the effective and efficient achievement of the desired strategic goals and objectives.

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Chapter 4

An Historical Survey on Environmental Conservation Initiatives in Iringa Region, Tanzania, 1974–2020

Hezron Kangalawe

Abstract

With the growing climate change worldwide manifested mainly through deforestation as part of the increased human activities toward environment for earning life, some stakeholders have started addressing this problem locally and nationally. In Iringa region, Tanzania, some efforts have been put in place to overcome deforestation challenges by with having a ministry designed to deal with environmental conservation. Non-governmental organizations are dedicated to environmental conservations. These efforts have attracted less scholarship than the negative cases. This paper uses Iringa region which since colonial period attracted investors on tea, tobacco, plantation forests (by state and private actors) and avocados to explore the varied activities that have been in place between 1974 and 2020 in addressing environmental degradation. These efforts were divided between state and non-governmental actors. This paper uses primary documentary reviews and secondary sources to make its arguments. It was discovered that climate effects have been felt by majority of the people in Iringa and as a result, there have been efforts at the level of individuals, non-governmental organizations and the state to ameliorate climate by and planting trees. Tree planting was positive on the plantation forests as villagers wanted to gain economically.

Keywords: environmental conservation forest, tree planting, Iringa, environmental degradation, forests

1. Introduction

Iringa Region is an offshoot of the Iringa Military district of the German colonial regime going back to 1897.[1] After the pacification of the Mkwawa (paramount chief the Hehe ethnic group) resistance, in 1898 when he committed suicide at Mlambalasi area, the main focus of the colonizers (the Germans) was to bring colonial economic projects. The earlier colonial economic developments, however, were connected to

[1] See for example, Ref. [1]; See, also, Ref. [2].

environmental degradation done by "natives" of which it was ostensibly a justification to land alienation and, indeed, expanding their economic spheres. By the early 1920s, some crops proved to grow well in Iringa Region, albeit with complaints by the settlers and planters on the shortage of laborers and environmental degradation.[2] These settlers introduced two major cash crops, namely, tea and tobacco, in the currently Mufindi and Iringa districts, respectively. Tea and tobacco needed a climate that was well taken care of and food for laborers in these projects. As a consequence, by 1940s when tea was in its peak, the Isimani maize scheme was well supported by the state as maize farming locally ensured food security internally and for export. The project was well commended by the British government as after the Second World War (1939–1945) and the Great Depression (1929–1939), food was highly needed in many places, locally and internationally.[3] The project, however, proved to be a disaster to the local environment in Isimani; henceforth, this paper surveys some measures that were employed to address the problem.

2. Methodology

The data for this chapter were obtained through archival sources–a methodology that is crucial for historians and some scholars in the social sciences such as Anthropology and Sociology. The methodology is usually corroborated with oral interviews. The archival sources were read at the Tanzania National Archive–Dar es Salaam and at Sao Hill Forest Plantation with its Headquarters in Mufindi district in Iringa Region. Interviews were administered in the three districts of Iringa Region, namely, Mufindi, Kilolo, and Iringa, and of course in Dar es Salaam City (where every region in Tanzania has a representative people because it is the economic hub of the country) between 2016 and 2023. Parts of these data were initially collected as part of the main project of my doctoral thesis.[4] The data obtained were analyzed qualitatively and corroborated each other to develop the measures taken by individuals, nongovernmental actors, and, indeed, the state in addressing the problems of climate change in the three districts of Iringa Region. The intensity of the measures differed from one district to another depending on the volume of degradation and, indeed, depending on the economic projects established. After completing the main project (PhD thesis), it was noted that the main mission of all these environmental engineering in the form of plantation forests, maize, tea, and tobacco farming might be collected and analyzed systematically and chronologically in a single chapter historically. Henceforth, the current chapter tries to weave together efforts rendered by different stakeholders *via* written records (archival and non-archival materials) at hand and, indeed, by interviews as a way of corroborating the truth contained in the archival records. While archival sources were the foundation of this chapter, interviews were equally important as they stroke the balance and, indeed, remove the bias of written sources. Historical survey as opposed to other disciplines was employed to navigate environmental conservations as it reflects well the factors behind the efforts taken over time[5] (**Figure 1**).

[2] See, for example, Refs. [3, 4].

[3] See, for example, Ref. [5]; Ref. ([6], p. 90). Ref. [7].

[4] See, for example, Ref. [8].

[5] Ref. [9].

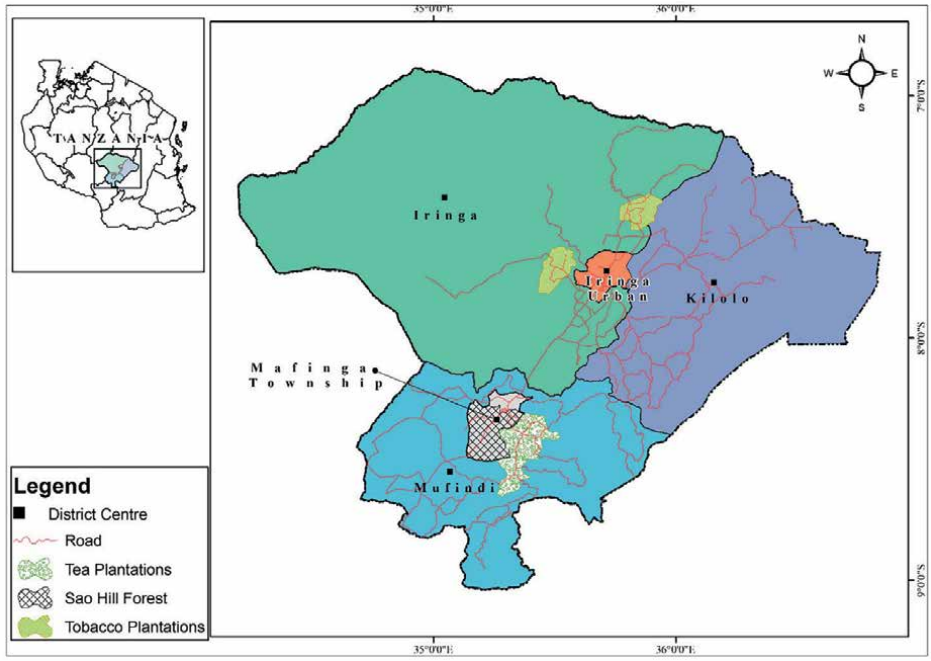


Figure 1.
Iringa region showing tea plantations and tobacco plantations (Source: Geography Department, Cartographic Unit, University of Dar es Salaam, Tanzania, 15.2.2024).

3. Economic projects and human activities in Iringa region, 1974–1990

Iringa Region has been the home of many economic activities that have contributed significantly to economic development as well as environmental degradation. These included projects that with history going back to the colonial period especially during the British colonial administration. The earliest project that was established during the Germany period is tea, which from its beginning to the present uses woods in its factories to burn its green leaf to get made tea. The history of tea in Iringa Region as a cash crop goes back to 1928 when the German settlers started their farms in Mufindi highland in the southern part of the district. However, tea was first introduced to the Southern Highlands Province in 1904 when a small parcel of seed obtained from Ceylon (Sri Lanka) was planted at Kyimbila Mission in the current Rungwe District in Mbeya Region. From this introduction, seedlings were obtained in 1913 and planted in the field at Kyimbila. During the years 1924–1926, seed from Kyimbila trees was planted at Musekera Estate within the district. Further importation of seed from Assam (India) occurred between 1926 and 1928 when development on a larger scale commenced, but planters turned to tea planting as an alternative to coffee planting much later. To assist the planters, the government distributed seedlings without charge in Rungwe and Mufindi districts during the years 1930–1934.[6]

Tea growing on a commercial basis started in 1928 when the provincial commissioner of Iringa wrote to the chief secretary of the Tanganyika territory government on tea growing in Iringa province that it was proving as a cash crop in the region.

[6] Tanzania National Archive (TNA)—Southern Highlands Province Provincial Book Report Volume II.

The provincial commissioner asked the colonial government to direct the director of agriculture to plan for a scheme of tea growing industry by means of cooperative experiment between the Department of Agriculture and the selected settlers who were already on the ground.[7] The provincial commissioner tried to convince the chief secretary by putting it in this way:

> *This scheme appeals to me especially because tea growing industry which according to the information available appears to be likely to pay very well is certain to attract good class of settler and capital from a wealthy industry to the high rainfall area of the [Iringa] province. The climate is cool and humid and therefore good for tea production. There are very few natives who reside in it, and those who do, have no objection whatever to disposing of their rights to incoming settlers. The agricultural survey has just been completed in Lupembe, Mufindi and Dabaga.*[8]

Later, tea seed to Mufindi to increase production was transferred from India *via* Mombasa to Tanga–Korogwe–Kondoa Irangi and then to Iringa by Bell who had started an experiment earlier at Marikitanda in Amani since the German era. It was Bell who was commissioned by the government to study and report on the prospects of tea planting on the southwestern highlands of Tanganyika. His field investigations and the subsequent report concentrated on Dabaga, Mufindi, and Lupembe of the present-day Kilolo, Mufindi, and Njombe districts, respectively. The report concluded that the whole area was good for tea production, but the only anticipated drawback was cold climate. Bell made a detailed study by making a comparative study basing on the climatic condition of the Kenyan plantation of Nderi Estate in Limuru and the Ambangulu Estate in the western Usambara of Tanganyika.[9]

Bell's report further suggested that the government had to create a conducive environment for laborers since tea planting required very many laborers. Bell put it this way in his report:

> *We may dismiss the question of suitability of climate right away, as the African natives have already proved to satisfaction that they compare favorably with the Tamil labourers of South India who is the race chiefly employed on the plantations... provided that the settlers make up their minds to treat labourers really well. That is to say good pay, full rations, or cash equivalent, really good housing, proper medical attention and all possible help and encouragement to parents and even care of native children.*[10]

Another stimulus to the young tea industry in Mufindi was provided by a report by Mann in 1932. Mann was an eminent authority on tea matters who had been commissioned by the government to make a further study on the possibility of expanding tea production in Iringa District and some parts of Njombe District. On the whole, he was in agreement with the Bell's report except that he did not think Dabaga was suitable for growing tea. He also recommended that due to transportation difficulties and given Lupembes' location (almost 60 km east of Njombe town center) to him, the area was not very suitable for tea. That reason worked in the planters' interest, which

[7] TNA, Accession No. 24: Tea Industry in Iringa.

[8] TNA Accession No. 24: Tea Industry in Iringa.

[9] Ref. [10].

[10] Robert Mabele, 13.

favored Mufindi area than Dabaga and Lupembe.[11] It was the report of Mann that led to tea production on a commercial scale in Mufindi. The only barrier was the financial means of the planters, which limited the extension of entering the territory into the World Tea Registration Scheme in 1934. As a result of an Ordinance being passed, tea could only be planted under license. It was large firms in Germany that became interested in tea production in Mufindi and thus financed the planters.[12]

This long story of tea establishment in Mufindi, a district of Iringa region, signifies that the region's environment was part of colonial economy and hence protecting it was equally important. Around these tea plantations, it was advised by environmental experts to plant windbreaker trees and Eucalyptus for tea-curing process. Above all, the tea companies were educated on maintaining pockets of natural vegetation as part of ameliorating the climate.[13]

Tea factories were still using woods for drying tea leaves. However, by 1970s, due to shortage of the natural forests around Mufindi, there was a campaign for almost all tea companies to planting eucalyptus for drying tea leaves in their factories. By planting eucalyptus for being used in drying tea in their factories, they assured that the speed of cutting natural forests was reduced.[14]

4. Iringa region and environmental conservation efforts, 1990–2010

The conservation of many parts of Iringa started in the 1990s after the structural adjustment program brought in by the World Bank and the International Monetary Fund (IMF), which encouraged sustainable investment in the environment. In Iringa Region, it was at this time that major economic projects were advised to abide with environmental guidelines. In this regard, the companies/big companies that were connected with environmental degradation such as those of tobacco farming in Iringa district and tea farms were encouraged to plant their own trees for curing tobacco and tea. On other occasions, they were advised to use electricity of the national grid, TANESCO (Tanzania Electricity Supply Company).[15]

On the other hand, the non-governmental organizations in Iringa region assisted the government on educating and sensitizing the citizens on sustainable agricultural production and natural resource management. This role was well-done by a Norwegian-funded non organization, namely, in Swahili as *Hifadhi Mazingira* (HIMA), which can be loosely translated as "Conserve your environment". This non-organization started officially in Iringa Region in 1990 before spreading to other districts of the then Iringa region, which included the currently Njombe region on which Makete, Wanging'ombe, Njombe, and Ludewa were included.[16] The project ended in 2002. The project, inter alia, educated the rural people on animal husbandry, good crop cultivation, soil and water conservation, forestry practice, and production. Masses of the villagers in the rural areas were taught the proper management of land and increase productivity per acre.[17] Above all, to ensure that these projects

[11] Robert Mabele 14.

[12] TNA Southern Highlands Provincial Book Report Volume II.

[13] Interview with Kasian Chang'a, Idetero Village, Mufindi, 15.12. 2023.

[14] Interview with Kassian Chang'a, Itona Tea Factory, Mufindi district, 12.11.2023.

[15] Interview with Emmanuel Kihongo 24.3.2023.

[16] Ministry of Foreign Affairs of Denmark, (DANIDA, 2007), 7–11.

[17] Interview with Johnson Mdagachule, Makambako Town, 25.10.2023.

last longer, the HIMA project brought in women empowerment and gender equity in these districts.

There was another nongovernmental organization that worked closely with the people in the Isimani area to do conservation of environment because of the threat of deforestation and desertification done by expanding maize farming in the late 1980s. CONCERN, was an international organization dealing with poverty eradication. Poverty eradication according to this organization was by conserving soil that was of low productivity. It was further argued that when the farmers protected their farms from land degradation, crop harvest would increase; henceforth. Their gross income was expected to increase more. These interventions are very much remembered by the local population because they introduced new tree species that were user-friendly with the soil of Isimani division.[18]

On the peasantry agriculture, the government educated villagers to use manure so as to increase land productivity and also abide with the agroforestry policy that encouraged them to divide their farms into different parts of their agricultural needs. The government circulated bylaws to persuade the villagers to abide by agroforestry practices whereby every household would have to divide its land into sections for food crops, forestry, and those with livestock they were to set a piece of land a grazing. Without such stern measures, the region was likely to go into a semidesert status.[19] The idea of using agroforestry was cemented by an agroforestry professor from Sokoine University of Agriculture. Luther Lulandala was quoted saying "agroforestry is the solution for all problems related to fire woods and hunger, as everyone would produce the needy items at his/her farm."[20] This has been the practice for many peasants in Iringa Region nowadays. They are no longer waiting to fetch firewood for cooking in the natural forests but rather harvesting from their own woodlots within their customary land. They had planted trees from the emphasis brought by the state and by seeing the early woodlot planters' benefits.[21]

In Isimani area, where maize farming started seriously after the Second World War,[22] the farming process led to clearance of many of its natural vegetation. Peasants emulated what they were told by the nongovernmental organizations and by planting trees. Because Isimani area is a semi desert peasant were educated on planting trees which that could grow well in that area. Yet there were reports of some village leaders who were prohibiting these free environmentalists in planting trees in their traditionally owned lands, despite the exhaustion.[23] There was another group of individuals as well as the middle-class people who were from Iringa Region but staying in Dar es Salaam who were pro-green environment who organized a fund raising *via* social medias (WhatsApp and Facebook) of which many people were enthusiastic to contribute and some were even ready to take part in planting trees to reclaim the lost green vegetation. The main challenge in this direction especially in the Kilolo district was that the planting was pro-plantation forests than natural forests. Therefore, while the campaign to planting trees was vibrant in many people from Iringa, the main challenge was that of planting trees that were pro-moneymaking than returning its natural vegetation.

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[18] See, for example, Ref. [5].

[19] Interview with Jowika Kasunga, the then Mufindi District Commissioner, Mafinga Headquarter, 18.5.2016.

[20] Interview with Prof. Luther Lulandala, Sokoine University of Agriculture, Morogoro Region, 7.1.2016.

[21] Interview with Simon Ngenzi, Ihalimba village, Mufindi, 2022.

[22] For a detailed narrative on maize farming in Isimani, see, for example, Ref. ([6], p. 90).

[23] Interview with Kihogosa Nyenzi, Iringa town, 20.5.2022.

5. Environmental efforts towards addressing the degradation, 2010–2020

Iringa Region became one of the major regions for exporting timber by 2010s. This signified that the desire for planting trees increased tremendously. The leading region in the Southern Highlands was Njombe, making Iringa the second with Mufindi and Kilolo taking the lead [8]. With the growing high demands of construction materials internally and externally, the people of Iringa planted many trees to respond to these demands that are, in a way, part of addressing the environmental degradation.[24]

The income of the people of Iringa Region, specifically in many villages of Mufindi and Kilolo districts, was directly or indirectly connected to forest products and/or non-timber forest products. For example, the then district commissioner said to the author that "everyone in Mufindi district was a forester *knowing or unknowingly*" (author's emphasis).[25] The situation of planting trees in Iringa region was similar to what happened in Asia at Kumaon highlands in the Western India Himalayas whereby rural areas' people at the beginning of mass campaigns on planting were slow to adhere to afforestation between 1911 and 1916. After the long process of campaigning on planting trees *via* the local governments, the villagers became stakeholders of environmental conservations as the case for Mufindi. Before these initiatives, the villagers used fire as a weapon to threaten government measures in addressing degradation processes ([12], pp. 1–26). To emulate this example from Asia, it was noted that in the Iringa district where there were big maize plantations in the Isimani division and tobacco plantations by Greeks way back to 1940s to early 1970s, people had at the beginning were not enthusiastic to plant trees but after seeing the benefits they started planting trees which could grow in their environments. Individual farmers had decided to use terracing in their day-to-day maize and tomato farming. Terracing was once one of the main cause of villagers' resistances to the British colonial rule policy on environmental conservation in the Uluguru Mountains, in Morogoro region.[26] The people of Isimani have learnt this through nongovernmental organization that went to give public education on environmental degradation and the measures to mitigate.[27] Farmers in these areas of Iringa district were alarmed by the decline of food crops harvests; hence, they decided to use agroforestry measures in their farming.

The Mufindi district administration was well concerned with the environmental conservation in the rural areas to the extent of formulating a by law on use of terracing in the farms in the slops and practicing mixed farming in the whole district. The administration argued that the farmers were to be educated on avoiding monoculture agriculture where peasants produced a single crop for many years without changing. Added to that was the proper grazing methods as it was noted that the peasants who owned cattle used vast of hectares for grazing a process, which not only increased environmental degradation but also hardened the lands.[28] The opinion of the Mufindi district was shared by an agroforestry expert and a researcher at the Sokoine University of Agriculture. The expert was quoted as saying "agroforestry is the

[24] See, for example, Ref. ([11], pp. 74-100).

[25] Interview with Jowika Kasunga, former District Commissioner, Mafinga Headquarter, 18.5.2016.

[26] See also, for example, Ref. ([13], pp. 152-169); See also, Ref. ([14], pp. 126-134).

[27] Interview with Christian Mpalanzi, Chairman of "AvaHehe Lutogo Group" Dar es Salaam, December, 2023.

[28] Interview with Jowika Kasunga, the then District Commissioner, Mafinga Headquarter, 18.5.2016.

panacea for all problems related to fire woods and hunger, as everyone will produce the two items at his/her farm".[29]

Generally, at this phase, environmental conservations were given higher priority in Iringa region as some of the people in the rural areas were benefitting from activities related with forestry-related activities. Some villagers in Kilolo and Mufindi districts were acting as middlemen for land buyers from within their villages and from towns. The middle men benefited as there were certain amount of money they accrued as per their business.[30] Moreover, it was noted that many villagers who had planted their trees earlier of at least 6 years were selling their logs to the people who wanted to buy them, and it was noted that the Chinese were becoming good customers of such logs.

Though the current literature does not show that Tanzania is one of the countries that host a considerable number of Chinese engaged in forest-related business, the reality on the ground is that Mufindi district host a big number of these Chinese in Chinese. These Chinese were becoming a factor for land use change as many people were planting trees to be sold to the Chinese timber and plywood's factories. In Mufindi district, the Chinese had their presence through investing in more than 20 timber-related factories at Mafinga town (the headquarters of Mufindi district) and its outskirts.[31] The Chinese had invested in making plywood for the internal and external market. From Mafinga town Chinese factories, it seemed that the aims for the establishment were for exports to China (their home country). This was due to the fact that China was becoming the major player in the global forest products market, both as a producer and consumer. The Chinese investment in natural resources especially in forests in Africa is not new, however, as they have been exploiting natural forests in Mozambique, Sierra Leone, and DRC ([15], pp. 155–162, [16], p. 309). The current case of Tanzania is new as the Chinese are investing into state- and privately-owned plantations. These investments started in early 2010s; however, plywood factories started effectively by 2015 were galvanized by the ever-increasing demands of construction materials in China, which had imposed a ban on logging their own forests as part of broader efforts to protect its forests ([17], p. 151). In Mufindi district, they started by buying state-owned logs in the Sao Hill Forest before turning to the privately owned forests mainly eucalyptus and pines species. By buying the native logs, indirectly, it meant more planting of trees in the district. Interestingly, the Chinese enterprises at Mafinga town were loved by private woodlot developers as they found them a fine solution for their trees that were once rejected by timber businesspeople of which they (timber traders) claimed that their logs were not straight enough for timber. The Chinese were acknowledged to be the opposite buyers as they bought "every size of tree, straight and crooked." Because of this nature of the market of logs, villagers from Mufindi and Kilolo districts were lured directly and indirectly to increase the acreage of plantation forests. By increasing the acreage of trees to meet the Chinese market, they increased the number of lands that were under plantation forests. The bottom line of this argument is that the Chinese factories based in Mafinga town have assured the foresters (state and private) of the readily available market; hence, almost everyone would like to plant trees to meet the demands of the

[29] Interview with Professor. Luther Lulandala, Sokoine University of Agriculture, Morogoro Region, 7.1.2016.

[30] Interview with Ezekiel Mduda, Mfukulembe Village, Iringa district, 12.5.2023.

[31] Interview with Adriano Mwenda, Mafinga town, 26.3.2023.

Chinese factories. In a way of responding to this market, indirectly, there was also signs of land grabbing among people themselves and sometimes with the state.[32]

When the villagers were asked about excessive planting of exotic trees—especially pines—in their food crop farms, they responded that their land was exhausted and the staple food crops they produced, maize and beans, had a lower market value than timber.[33] They cited the Chinese as key factor as they could easily get money as they sold trees of even 5 years for millions of monies. One elderly villager was heard as saying, "I can buy food for the whole year by selling only five big trees from my tree farm."[34] This narrative signifies that trees were more expensive than food crops. Indirectly, tree planting was changing not only the traditions of farming but also the identity of the local people who were used to the cultivation of maize and beans as staple food.

At Mafinga town among the Tanzanian timber traders, the Chinese were seen as a threat to their business as they (Chinese) bought logs from the woodlot owners the trees for higher prices than the Tanzanian timber business people.[35] The businesspeople claimed that the Chinese were likely to bring shortage of timber for the construction industry in Tanzania in the coming years as their prices attracted many farmers to sell their trees at almost every age, and indeed, at the same time, the Chinese stimulated more tree planting in the rural areas of Mufindi and Kilolo districts of Iringa Region. While the timber business had all these allegations towards the Chinese traders, the farmers were very happy with the presence of Tanzanian the Chinese as they claimed that they benefitted more than the "exploitative" prices of Tanzanian timber traders of Mafinga town. In essence, the price of logs doubled when the Chinese opened their factories. Above all, the Chinese were congratulated for opening the best hardware shops at Mafinga town of which the surrounding community acknowledged that it had genuine simple machines for their timber industry. All these deeds by the Chinese added to more pressure on land for more afforestation and indirectly increased the size of afforested area in the region, and henceforth, these efforts are well acknowledged as new wave of planting trees. This is what scholars such as Jacovelli referred to as the undefined "new wave of investors in the forestry sector."

The knowledge of the villagers on planting trees in their woodlots, however, proved to be very low. Therefore, a large number of the villagers who planted trees in their farms were more or less forced to plant to respond for the market forces availed. Above all, they had no capital to buy land or new technologies for expanding their woodlots. Through planting those trees, they ameliorated the climate of Iringa Region. The farmers had woodlots with trees ranging from 5 to 20 acres.[36] These villagers and, indeed, some forestry staff members in Mufindi and Kilolo districts were more than willing to reveal the size of their tree farms. Many were proud to reveal the size of their farms possessions as it was a manifestation of high social status in their communities. Some village leaders were having their tree farms as well. At Nundwe village, one village executive officer was quoted saying that "I have already bought my piece of land in the village through village elders and I planted five acres

[32] Interview with Jonas Choga, Nundwe Village, 20.5.2021.

[33] Interview with Kambaulaya Mtavangu, Mtili Village, Mufindi, 19.5.2021.

[34] Interview with Zachary Kabogo, Lyasa Village, 10.9.2023.

[35] Interview with George Mwagala, Mafinga town timber traders, 27.1.2021.

[36] Interview with Raphael Lutumo (70 years), Ihalimba Village, 6.4.2016.

of pine [*Pines Patula*] trees".[37] Their understanding was that it was a shame for any inhabitant in Iringa Region to own no tree farms.[38] Therefore, owning trees farms in Iringa was slowly becoming a cultural identity of the region and beyond. Some youths at Bomani area, a timber-trading center in Mafinga, went further by suggesting the author to buy their land for planting trees as well. It was noted that beyond being agents in the timber-trading center, they were also agents of land selling and transfers in the rural areas. Therefore, the salient feature of the love of education on planting trees in these three districts of Iringa Region was that the farmers engaged with the planting of trees during the rainy seasons especially in Mufindi and Kilolo districts. In the semiarid areas of Iringa district, the villagers engaged with tomato farming. It was in the tomato farming that the use of terracing was emphasized by nongovernmental organizations and the state. One tomato grower in Isimani division was heard as saying, "my one-acre farm is producing more tomatoes after abiding with agroforestry and terracing measures."[39]

These villagers who planted trees for timber and for protecting erosion prepared their own seedlings. Some of them especially those from Mufindi were subsidized with seedlings they got from Sao Hill Forest and *Panda Miti Kibiasahara* organization.[40] With regard to proper silviculture practices, the knowledge of tree farmers was of low quality.[41] The village farmers had poor spacing of trees as they admitted that they were not educated about tree planting. The ministerial officer responsible for plantation forests at one time told the author that the poor knowledge of the farmers was to be solved by the district forest officers. With regard to this case, the district forest officer in Iringa district testified by saying, "we are underfunded to the extent that we cannot visit the private forest developers in their villages."[42] The district authorities' foresters in Tanzania were administered by the Ministry of Regional Administration and Local Government, which was and still is the biggest ministry in Tanzania; henceforth, the foresters had less priorities. Yet despite of all these problems, the private forest developers could make the three districts green by planting trees in their respective villages. There were few advanced ones with regard to knowledge and capital on forest development. These could buy land and plant trees. On the ground, few were people around the districts, while others were from far away such as Dar es Salaam, the business hub of the country. These private farmers were concentrated at some villages such as Mapanda in Mufindi district. Mapanda village was cited as the best village for planting trees in Mufindi district, albeit with complaints of land grabbing with well-to-do people allegedly with politicians being involved in the saga.[43]

The villagers harvested these trees whenever they thought they could get any wood of any girth. One timber-trading woman at Mafinga town was quoted as saying, "the villagers are forced to rape these young trees because they are pressed with financial problems like school fees for their children." She used the term "rape" to imply the young trees were prematurely harvested by the villagers.[44] The Ministry of Natural

[37] Interview with Godfrey Mkongwa, Executive Village Officer, Nundwe Village, 6.4.2016.

[38] Interview with George Mwagala, Timber trading centre at Mafinga, 18.5.2016.

[39] Interview with Samweli Kimbe, Isimani division, 26.4.2023.

[40] Interview with Robert Makuka, Kinyanambo, Mafinga urban, 24.4.2023.

[41] See, for example, Ref. ([18], p. 18).

[42] Interview with Prosper Njau, Iringa district Forest Officer, at Iringa district headquarters, on 14.5.2016.

[43] See, for example, Ref. [11].

[44] Interview with Maula Chaula (51), Mafinga Timber Trading Centre, 18.5.2022.

Resources and Tourism spokesperson on plantation forestry was of the opinion that the woodlot developers from the adjacent villages benefitted from knowledge disseminated by the Sao Hill plantation by coincidence. It was by coincidence as the aim of educating the villagers by Sao Hill Forest management was not to make them full-fledged foresters but at least to make them have low skills of developing their own trees so that they can depend on themselves rather than relying on the state forest—Sao Hill. He said that before 2000, there was a tendency among the villagers to depend on the Sao Hill plantation for everything.[45] He revealed that the ministry had once organized a workshop on harvesting technology for the surrounding community. Mathias Lema sympathized with the village woodlot developers by saying the right foresters who were meant to assist the village woodlot developers were the district foresters, but they were arguably underfunded. One district forest officer was quoted as saying, "we are underfunded to the extent that we have failed to visit the woodlot developers in their respective farms."[46] By being administered by this ministry, their importance was very limited as the ministry had many sub dockets to deal with. Above all, the politicians (councilors and members of parliament), who served for a five-year tenure, were, sometimes, not proactive in long-term projects such as forests planting.[47] Because of such problems in the local administration in Tanzania, many foresters preferred to work under the Ministry of Natural Resources and Tourism, where, according to them, they could utilize their potential to the maximum. They were underutilized, and indeed, they were a disappointed group.[48]

While planting trees was becoming a panacea for many individual as they benefited by getting money through increased crops and directly selling of timber at state level, the main investors in the region were also well monitored through laws and bylaws to ensure that they abide with environmental conservation measures. The tobacco farmers in Iringa district, for example, who were curing their tobacco from the natural forests were advised to stop and use other alternatives that were not detrimental to the environment.[49] They were advised to use woods from Sao Hill plantation forest. Sao Hill plantation forest is the biggest owned solely by the state and was one of the projects that benefited from foreign aid—especially from the World Bank, which provided loans for two tenures (1976 and 1982). The provision of these loans by the World Bank between 1976 and 1992,[50] a period of economic problems in Tanzania, ensured the survival of this plantation forest, which is an asset in the Ministry of Natural Resources and Tourism.[51] As private planters increased, other woods for curing were obtained from Kilolo district. The woodlot developers enjoyed another circulation of money by selling their logs to the tobacco farms. Above all, the tobacco farmers used electricity to cure their tobacco.[52] All these measures were part of embracing environmental conservation in Iringa Region.

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[45] Interview with Mathias Lema, TFS (Tanzania Forest Services Agency) Department, Ministry of Natural Resources and Tourism Headquarters, Dar es Salaam, 22.5.2016.

[46] Interview with Prosper Njau, Iringa district Forest Officer, at Iringa district headquarters, on 14.5.2016.

[47] Interview with Prosper Njau, Iringa district Forest Officer, at Iringa district headquarters, on 14.5.2016.

[48] Interview with Prosper Njau, Iringa district Forest Officer, at Iringa district headquarters, on 14.5.2016.

[49] See, for example, Ref. [7].

[50] The 1976 loan was aimed at maintaining and expanding the plantation forests established during the colonial period, while the 1982 loan was an appraisal loan for the mooted pulp and paper mill in Mufindi.

[51] Ref. ([19], pp. 149-160); Ref. [20]; Biermann, Werner, and Campbell, John. *The Chronology of Crisis in Tanzania*; 1974–1986.

[52] Interview with Emmanuel Kihongo, University of Dar es Salaam, 24.12.2023.

6. Conclusion

This chapter has used Iringa Region in Tanzania because of its big number of agricultural economic projects to gauge the level of awareness of the state, non-governmental organizations, and individuals on environmental conservation. The article used archival sources and oral interviews that were corroborated by secondary sources. Basically, the paper has argued that Iringa Region had a precedent of colonial economies that were taken over by the independent government way back in 1962. These agricultural colonial projects were in form of settler economy or plantation. Some of these colonial projects such as that of Sao Hill Forest were brought in Iringa to ameliorate the environment, which were deemed brought by the type of agriculture of the natives. This chapter therefore goes against this colonial thinking by arguing that there are various efforts in Iringa conducted by the state, nongovernmental organizations, and individuals in the process of environmental conservation. The initiatives are many, but not limited to, conducting awareness by the state and by nongovernment organization and individuals. The peasants have heeded to these orders brought in by the state; hence, they have become participants in environmental conservation in the region, albeit with economic motives as the readily market for timber-related products has lured them. In essence, this chapter argues that though there is huge scholarship on environmental degradation in Africa, it is equally important to acknowledge the various efforts taken by individuals, nongovernmental organizations, and, indeed, the state in ameliorating the climate, by using the case of Iringa Region in Tanzania.

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Chapter 5

Protected Area Size Affecting Habitat Fragmentation: A Case Study of Protected Areas in Thailand

Krisanadej Jaroensutasinee, Mullica Jaroensutasinee, Orranan Chuachart and Elena Sparrow

Abstract

Habitat fragmentation is a big threat to biodiversity because habitat fragmentation reduces the total patch area, isolates the patches, and increases the edge of patches. The objectives of this study were to investigate how protected area (PA) size affects habitat fragmentation and what caused habitat fragmentation in the PAs. The study focused on 180 PAs in Thailand, including 58 wildlife sanctuaries and 122 national parks. The land use/land cover data of Thailand were acquired from the Department of Land Development of Thailand and used to quantify forest habitat fragmentation in terms of the number of patches, patch density, proportion of forest, and clumpiness index. There were significant linear relationships between the total area and number of patches and between total area and patch density. Large PAs, with a total area larger than 1, 600 km^2, had significantly lower patch density than medium and small PAs. However, 128 of the 180 PAs in Thailand were small-sized with high patch density due to agricultural expansion making up approximately 10% of the protected areas. Large PAs with a size of 1600 km^2 or larger are preferable over small PAs in order to reduce habitat fragmentation and contribute to biodiversity conservation.

Keywords: protected area, habitat fragmentation, patch density, clumpiness index, land use

1. Introduction

Habitat fragmentation leads to biodiversity loss and extinction risk resulting from a single large landscape broken apart into many isolated smaller patches [1, 2]. Habitat fragmentation drives habitats to shrink, ultimately resulting in habitat loss. This fragmentation limits the number of individuals in an area and affects species richness and abundance [3]. Habitat fragmentation increases the proportion of edge to the total area, causing the edge effect. This edge effect enables the stress of microenvironment variation to some species [4]. Fragmented habitats have a smaller total area, while some species need large home ranges to survive, for example, hornbill and jaguar [5, 6].

Although the landscape can become fragmented by nature (e.g., water bodies), human activities (e.g., urban and crop expansion) accelerate habitat fragmentation [7]. Protected areas (PAs), as defined by the International Union for Conservation of Nature (IUCN), are clearly defined landscapes managed to conserve nature by legal or other effective means [8]. Within PAs, policies are established to avoid disturbance, such as limiting human visitations and activities and deforestation. PAs are practical tools to prevent fragmentation by maintaining the continuity of habitats [9]. Thus, it is necessary to study factors that would maximize the effectiveness of PAs.

Thailand's lush rainforests are home to a vibrant array of biodiversity and provide crucial ecosystem services. Still, they face a growing threat: forest fragmentation and significant landscape changes in the last half-century [10]. Between 1945 and 2020, Thailand's forest cover substantially declined from 61 to 31.64% [11]. Breaking up extensive, continuous forests into smaller, isolated patches significantly impacts the country's sustainability. The significant causes of forest fragmentation in Thailand are agriculture intensification, infrastructure development and urban expansion, and resource extraction [12, 13]. Thailand's booming agricultural sector, particularly for agrarian commodities such as rubber, rice, oil palm, tea, sugar cane, corn, and cassava, has driven extensive deforestation, increased soil erosion in watershed areas, and desertification, fragmenting once-contiguous forests [14, 15]. Infrastructure development and urban expansion reinforce economic growth and captivate foreign investors for sustainable production and productivity. The Thai government invests in infrastructure supplemented by external financing, such as hydroelectric dams, roads, mining, telecommunications, airports, and oil and gas pipelines [12]. In the past, illegal logging and mining have been the primary drivers of Thailand's forest fragmentation.

Forest fragmentation directly affects environmental sustainability, resulting in biodiversity loss, disrupted water cycle, carbon stock reduction, and ecosystem service loss [16–19]. Thai forest area and fragmentations negatively correlated with three environmental parameters: temperature, rainfall, and relative humidity [20]. Forest fragmentation gives rise to higher temperatures for three main reasons. First, deforestation releases carbon into the atmosphere, increasing greenhouse gases and global temperature [21]. Second, highly fragmented forests generate a lower rate of evaporation and photosynthesis in the forest, increasing the temperature in the atmosphere [22]. Third, forest fragmentation alters cloud-formed condensation, wind, and water flow, causing higher temperatures and drier areas [22]. In addition, forest fragmentation also leads to reduced rainfall and relative humidity [23]. An intact forest landscape produces high rainfall and relative humidity from plant photosynthesis and transpiration processes [24].

Forests are an important ecosystem and key economic sector in Thailand, bringing 3.9 billion USD in exports in 2020 [13]. The Thai government aims to raise the national forest cover to 40% by 2036 by protecting intact forest landscapes, preventing forest fragmentation, and promoting sustainable practices [25]. This study investigated (1) how PA size influences habitat fragmentation within their boundaries and what size of PA is enough to slow down habitat fragmentation and (2) which human activities expand into and disturb PAs by studying the land use/land cover (LULC) in PAs. This study helps us better understand the effectiveness of PA size to support making effective administrative policies, PA plans, and PA design.

2. A case study of protected areas in Thailand

2.1 Study area

This study included all 180 PAs in Thailand, composed of 58 wildlife sanctuaries and 122 national parks. Spatial data of the PAs were downloaded from the World Database on Protected Areas (WDPA) [8] in shapefiles. According to the IUCN, PAs were classified into six management categories of I–VI (with Ia and Ib as subdivisions). Still, Thailand had only five categories of PAs (Ia, II, III, IV, and VI). In this study, we focused on two of the most strict PAs: Ia PAs were "wildlife sanctuary" and II PAs were "national park" (**Figure 1a**).

National parks differed from wildlife sanctuaries because they were less protected and allowed human visitation and recreation [26]. We divided the 180 PAs into three categories: small, medium, and large PAs using the Natural Break (Jenks) method [27]. The Natural Break (Jenks) method allowed us to categorize the PAs by minimizing class variance. With this method, the 180 PAs were divided into 123 small (24.372–618.974 km^2), 49 medium (618.975–1677.277 km^2), and eight large (1677.278-3730.748 km^2) PAs with a standard deviation of 14.4, 38.5, and 226 km^2, respectively. To further quantify habitat fragmentation, the land use/land cover (LULC) data of Thailand in shapefiles were acquired from the Department of Land Development of Thailand. The LULC data were analyzed from THEOS, Landsat 8OLI, Sentinel-2 satellites, and ground observation from 2019 to 2022. The LULC was classified into five types: forest land, water bodies, agricultural land, urban and built-up land, and miscellaneous land (**Figure 1b**).

2.2 Habitat fragmentation estimation

FRAGSTATS version 4.2 [28] was used to quantify habitat fragmentation in the PAs. To prepare files before analysis, the LULC shapefiles were rasterized into 30 × 30 m^2 cells by maximum combined areas cell assignment type. Habitats were defined as forest habitats, so LULC types other than forest land were selected as the background to create the binary forest and non-forest maps. The habitat fragmentation metrics were then calculated based on the eight-neighbor rule. Four class-level metrics were chosen: (1) the proportion of forest defined as the percentage of forest habitat in the total area of a given PA, (2) the number of patches defined as the number of isolated mosaics of forest land cells, (3) the patch density defined as the number of patches divided by the total area in km^2, and (4) the clumpiness index defined as the proportional deviation of the proportion of like adjacencies of the forest land from that expected if the patches were randomly distributed. The clumpiness index was 0 when patches were randomly distributed, 1 when patches aggregated, and − 1 when patches disaggregated [6, 29].

2.3 Data analysis

Simple linear regression was used to examine the relationship between the total area of the PAs and the four habitat fragmentation metrics (proportion of forest, number of patches, patch density, and clumpiness index). The Kruskal-Wallis test and Dunn's multiple comparison tests were used to examine the differences in habitat fragmentation among the three sizes of protected areas.

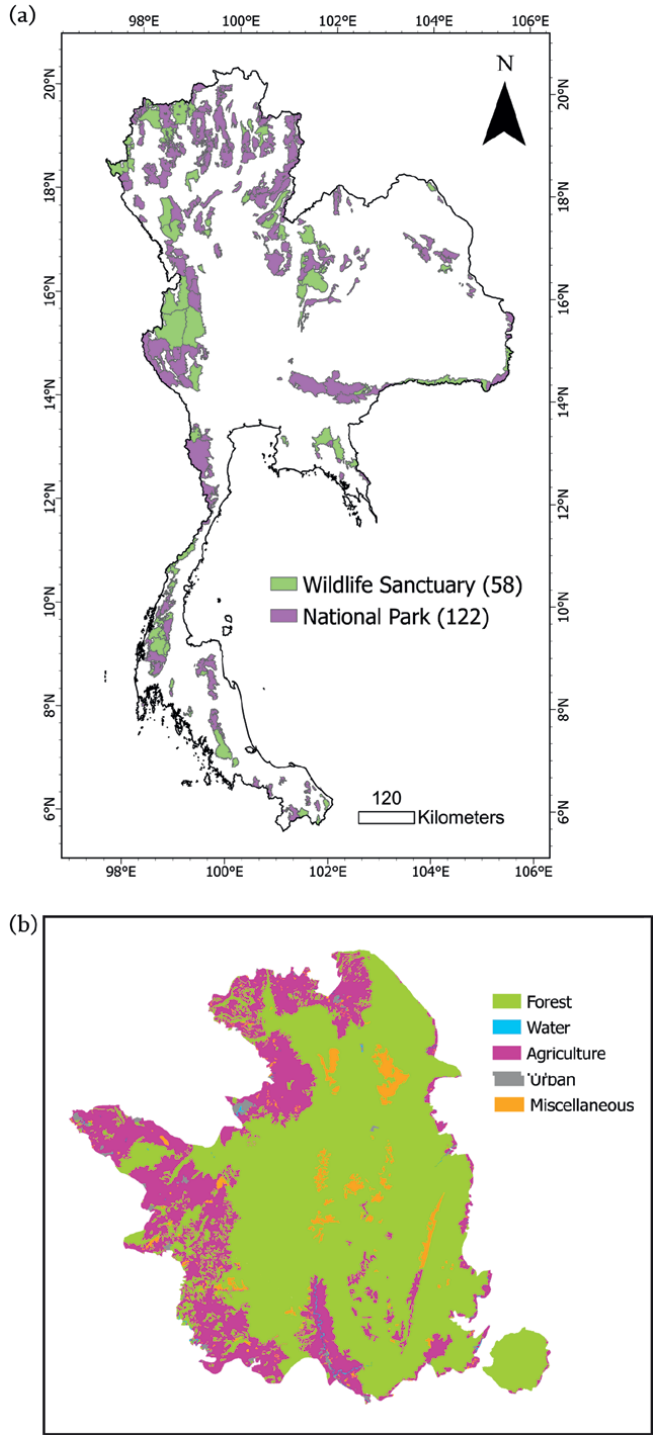


Figure 1.
Thailand map and protected areas: (a) 180 protected areas in Thailand (green = 58 wildlife sanctuaries and purple = 122 national parks) and (b) LULC types in an example for Phu Luang wildlife sanctuary with 5 LULC types (green = forest land, blue = water body, pink = agricultural land, gray = urban and built-up land, and orange = miscellaneous land).

2.4 Protected area size comparisons

The PAs in Thailand have an average total area, number of patches, patch density, proportion of forest, and clumpiness index equal to 583.45 km^2, 70 patches, 0.144 patches/km^2, 87.35%, and 0.83, respectively. They have a wide range of total area, with the largest at 3730.75 km^2 and the smallest at 24.37 km^2. The lowest proportion of forest habitat in a protected area was half (50.91%) of the total area. The number of patches in a protected area was as high as 432. The patch density ranged from 0.002 to 1.123 patches/km^2. There was a protected area with clustered patches (clumpiness index = 0.98) and one with dispersed patches (clumpiness index = −1.00) (**Table 1**).

Comparing the three PA sizes, the medium PAs had a higher number of patches than the small PAs, but there were no differences in others (Kruskal-Wallis test: $H_2 = 34.44$, $P < 0.01$; Dunn test: Z = 5.71, $P < 0.05$, **Figure 2a**). The large PAs had less patch density than both the small and medium PAs (Kruskal-Wallis test: $H_2 = 6.24$, $P < 0.05$; small PAs: Dunn's test: Z = −2.48, $P < 0.05$; medium PAs: Dunn's test: Z = −2.34, $P < 0.05$, **Figure 2b**). However, there was no significant difference between the PA size and the proportion of forest (Kruskal-Wallis test: $H_2 = 1.043$, *ns*, **Figure 2c**) nor between the PA size and the clumpiness index (Kruskal-Wallis test: $H_2 = 1.62$, *n*s, **Figure 2d**). The patch density of the wildlife sanctuaries (mean ± SD = 0.12 ± 0.11 patches/km^2) was significantly less than the national parks mean ± SD of 0.16 ± 0.14 patches/km^2, Kruskal-Wallis test: $H_2 = 3.87$, $P < 0.05$).

2.5 Total area affecting habitat fragmentation

Total area was positively associated with the number of patches but negatively associated with the patch density (simple linear regression: number of patches: $R^2 = 0.19$, $F_{(1,178)} = 41.07$, $P < 0.001$, y = 0.064x + 32.88, **Figure 3a**; patch density: $R^2 = 0.032$, $F_{(1,178)} = 5.86$, $P < 0.05$, y = −0.000043x + 0.17, **Figure 3b**). Total area was not associated with the proportion of forest and clumpiness index (proportion of forest: $F_{(1,178)} = 2.51$, ns, **Figure 3c**; clumpiness index: $F_{(1,178)} = 0.85$, ns, **Figure 3d**).

2.6 Land use/land cover types in the protected areas

Forest land LULC made up the highest proportion 88.06, 87.41, and 91.92% of the small, medium, and large PAs, respectively. The second highest LULC type was agricultural land, which comprised 9.56, 9.43, and 5.33% of the small, medium, and large PAs, respectively. The remaining LULC types (water body, urban and built-up land,

	Mean	Median	Maximum	Minimum	S.D.
Total area (km^2)	583.45	425.33	3730.75	24.37	565.37
Number of patches	70	41	432	1	84
Patch density (patches/km^2)	0.144	0.119	1.123	0.002	0.135
Proportion of forest (%)	87.35	89.88	99.98	50.91	10.23
Clumpiness index	0.83	0.88	0.98	−1.00	0.21

Table 1.
Habitat fragmentation metrics of the protected areas (n = 180) in Thailand.

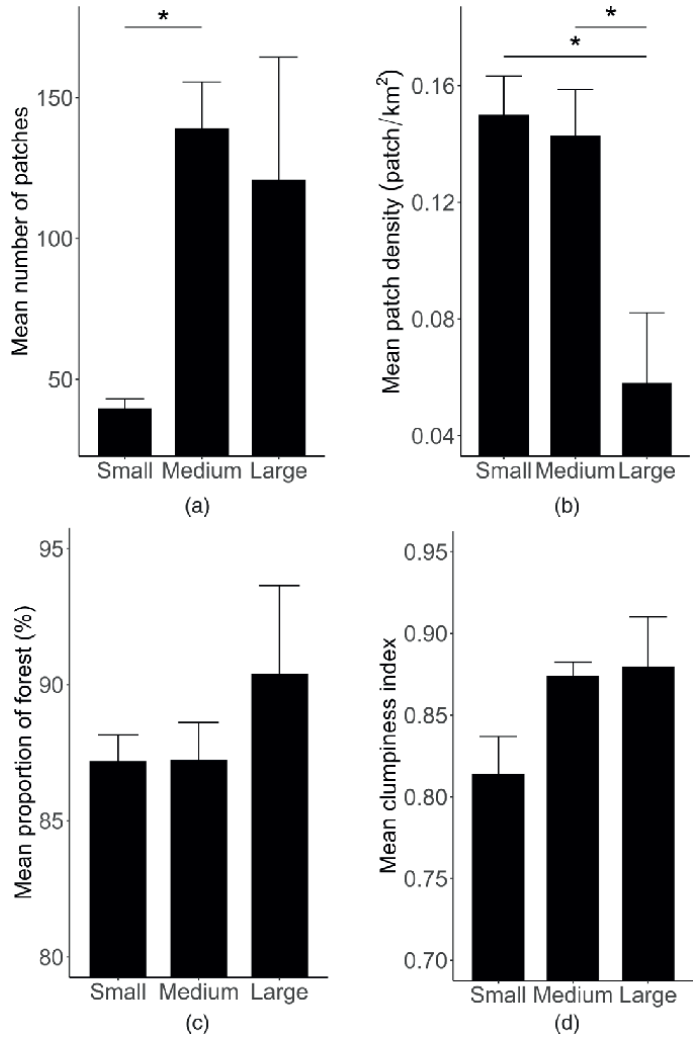


Figure 2.
*Habitat fragmentation metrics and PA sizes: Small, medium, and large sizes (*P < 0.05).*

and miscellaneous land) comprised only 2.38, 3.16, and 2.75% in the small, medium, and large PAs, respectively (**Figure 4**).

Results of this study revealed that the mean forest proportion of the PAs in Thailand was 87% which is comparable to 85% found in a previous study in Thailand [30]. The forest cover percentages in the IA and II PA categories were reported to be around 80% and 75% globally, respectively [31]. In our study, the mean patch density and clumpiness index of the PAs in Thailand were 0.14 patches/km^2 and 0.83, respectively. These metrics indicate that the degree of habitat fragmentation contributed to the adequacy of PAs for wildlife species. Low patch density and high clumpiness index show high connectivity in the PAs. The PAs with high connectivity increase subpopulation survival by allowing populations among patches to meet, mate, and forage successfully [5, 32].

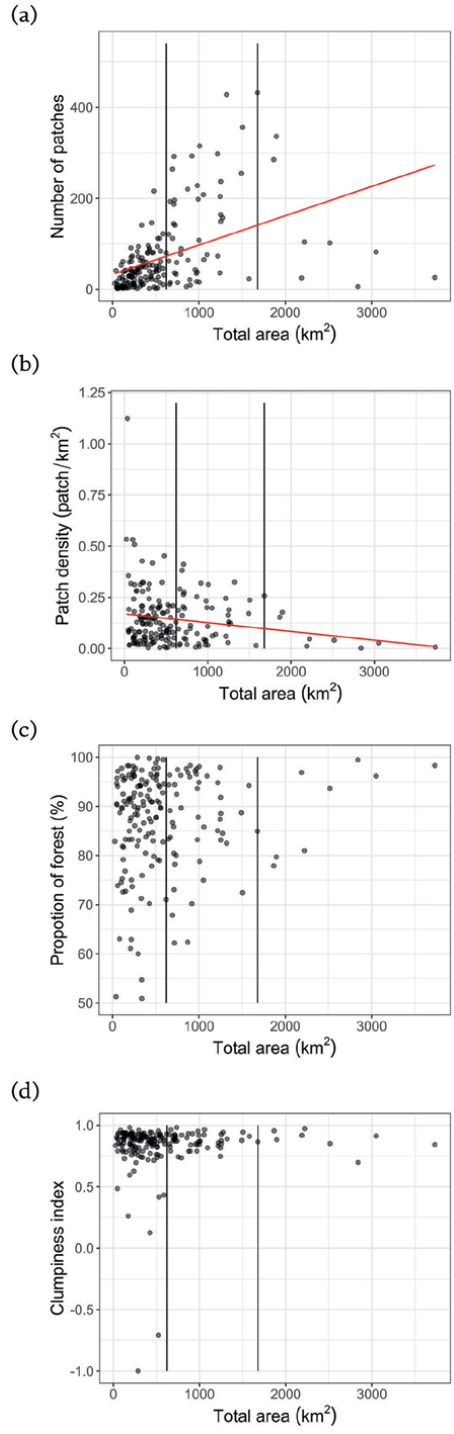


Figure 3.
Total area and habitat fragmentation metrics: (a) number of patches, (b) patch density, (c) proportion of forest, and (d) clumpiness index. Two black lines delineate small, medium, and large PAs.

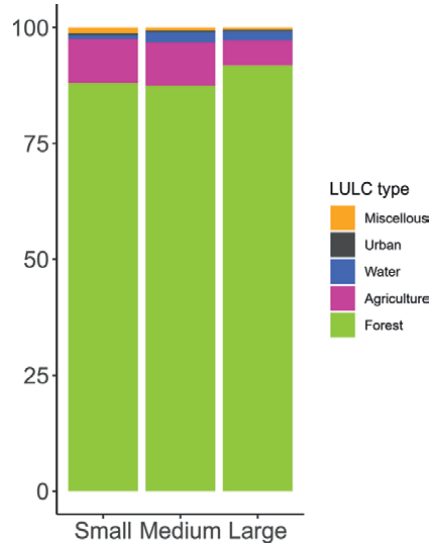


Figure 4.
LULC types in the small, medium, and large PAs (green = forest land, blue = water body, pink = agricultural land, gray = urban and built-up land, and orange = miscellaneous land).

Our study showed 123 small PAs out of 180 PAs, ranging from 24 to 618 km^2, indicating that most of the PAs in Thailand are small with high patch density. Small PAs with high habitat fragmentation lead to lowering the interior edge ratio, speeding up the breaking rates of small patches, reducing the mean patch size, and increasing the isolation among patches [1]. Our study also found that habitat fragmentation in wildlife sanctuaries was higher than in national parks because of management policy differences. National parks have stricter rules and regulations with severe penalties, for example, prohibiting human activities, closing to the public, and having fixed and defined park boundaries, compared to wildlife sanctuaries. Local people cannot collect non-timber forest products (e.g. honey, fruits, and berries) from national parks, preventing the downgrading of large-scale ecosystems, which is a cause of habitat fragmentation [33].

Our study is among the first in Thailand to demonstrate that PA size influences habitat fragmentation with a negative association. The results are consistent with previous studies [34, 35]. Our results indicated that, at least in Thailand, the PA size has to be larger than 1600 km^2 to slow down human activities such as slash-and-burn farming, rural development, and urbanization. Like many developing countries, Thailand's main habitat loss comes from converting forests to cropland for high-priced food [36, 37], rubber plantation, and biofuel crops. Besides causing habitat fragmentation, these planted fields can support fewer species than forests [38]. In addition, our results also indicated that some forest land has been converted to housing developments, roads, and industrial sites. Rural development and urban expansion in Thailand are related to road construction, leading to land use changes from forest land to agricultural land. The fragmented PAs may become too small to support large territorial species for their food and mates and for migratory species to find places to feed in their migratory routes. A key benefit of large PA size is preventing edge effect, which causes changes in microclimate and alters the ecological systems around the interior and exterior portions of the fragments [39].

3. Policies needed to reduce fragmentation in Thailand

Like many developing nations, Thailand faces the challenge of a fragmented landscape across various sectors. This fragmentation hinders efficient governance, economic development, and social cohesion. A multi-pronged approach involving policy interventions in different areas is crucial to address this issue. Here are some key policy considerations:

3.1 Land use and urban planning

Land use and urban planning are two key policies needed to reduce forest fragmentation in Thailand. The three key areas focused on are spatial planning, urban zoning, and infrastructure development. First, spatial planning implements comprehensive national and regional spatial plans that guide development around strategic centers, promoting efficient land use and reducing sprawl. Second, urban zoning can be implemented by reinforcing clear and transparent zoning regulations delineating areas for different activities, minimizing land-use conflicts, and promoting mixed-use development. Lastly, infrastructure development is another major driver of fragmentation. Prioritize investment in infrastructure networks (transportation, water, and sanitation) that connect fragmented urban and rural areas, fostering greater accessibility and economic integration.

3.2 Governance and institutional reform

Governance and institutional reform are needed to reduce forest fragmentation in Thailand. Three key focuses are decentralization, streamlined regulations, improved data sharing, and transparency. Decentralization can be undertaken by enhancing local government autonomy and capacity to manage their affairs while promoting intergovernmental coordination and collaboration to address regional challenges. Streamlined regulations can be employed by simplifying and harmonizing regulatory frameworks across different sectors and agencies, reducing bureaucratic hurdles, and promoting business environment consistency. Improved data sharing and transparency would foster collaboration and information exchange between government agencies, the private sector, and civil society to facilitate informed decision-making and address fragmentation challenges.

3.3 Economic development and social inclusivity

Economic development tends to work against forest fragmentation everywhere in the world. If Thailand can use economic development as a positive driving force to reduce forest fragmentation, we should focus on these three areas: target incentives, skill development, and social safety nets. For targeted incentives, Thailand should design and implement targeted incentives for businesses and industries to invest in underdeveloped or fragmented areas, promoting economic diversification and regional development. For skills development, we should invest in skills training and education programs that equip individuals with the skills to thrive in a globally integrated economy, reducing income inequality and social fragmentation. For social safety nets, strengthening social protection programs to address vulnerabilities and

ensure equitable access to opportunities for all, fostering greater social cohesion, and reducing inequality need to be addressed.

3.4 Forest management strategies for protected areas expansion

Expanding protected areas plays a crucial role in safeguarding Thailand's natural heritage and ensuring the long-term survival of its unique flora and fauna. The 1950s saw the Royal Thai government take decisive action against deforestation, establishing protected areas and launching dedicated reforestation programs, with a target of maintaining at least 50% of the country's forest cover (Thai Forestry Sector Master Plan, 1993) [30, 40]. Responding to rapid deforestation, the 1985 National Forest Policy set a 40% national forest cover goal, with 15% designated as strictly protected areas and 25% dedicated to sustainable resource utilization [10]. Thailand's unwavering dedication to environmental stewardship is evident in the impressive network of protected areas established in 2005. With 103 national parks, 84 forest reserves, and 55 wildlife sanctuaries stretching across the country, Thailand is a testament to preserving natural heritage for future generations [41]. With the National Park Act and the Wild Animal Reservation and Protection Act (2019) now in place, Thailand's stunning landscapes and abundant wildlife have a brighter future. These comprehensive laws equip authorities with enhanced tools to combat poaching, manage tourism responsibly, and promote sustainable practices within protected areas, laying the foundation for a flourishing natural heritage for years. Forest management strategies for protected area expansion in Thailand should focus on three areas: (1) collaborative landscape management, (2) ecological restoration and connectivity, and (3) science-based decision-making.

3.4.1 Collaborative landscape management

Collaborative landscape management is crucial in community forests and buffer zones. We empower local communities to manage and steward forests within their traditional territories, proven effective in reducing deforestation and promoting sustainable practices. Local communities will be planted with a sense of ownership and responsibility for their land, leading to improved conservation outcomes. By surrounding protected areas with a buffer of well-managed forest, connectivity between habitat patches operates as dispersal corridors, allowing for vital animal movement and gene flow and preventing demographic and genetic depression of resident populations [42]. Buffer zones around protected areas provide specific benefits: reducing habitat fragmentation, minimizing physical or chemical edge effects (e.g., agricultural pesticides, soil erosion, fires), promoting sustainable resource use, preventing encroachment, and protecting against encroachment and harmful activities like illegal logging and poaching [43]. Effective buffer zone management strategies have four key areas: community participation, land-use planning, livelihood diversification, and monitoring and enforcement. In many regions, securing adequate funding and resources for long-term buffer zone management remains challenging. Raising awareness and public support for buffer zone conservation is crucial for garnering wider commitment and participation. By effectively managing buffer zones, we can create a win-win situation for people and nature. These crucial transitional areas can safeguard the ecological integrity of protected areas while fostering sustainable livelihoods and promoting harmonious relationships between communities and the natural world.

3.4.2 Ecological restoration in Thailand: Reviving nature's tapestry

Habitat loss, deforestation, and unsustainable practices have fragmented landscapes and threatened precious biodiversity. Ecological restoration aims to heal damaged ecosystems, returning them to a state closer to their original biodiversity and functionality. Ecological restoration can involve various practices, from planting native trees and restoring degraded mangrove forests to controlling invasive species and reintroducing native fauna [44]. Engaging local communities in restoration efforts fosters ownership and long-term sustainability. Communities can participate in tree planting, seed collection, and monitoring activities, building a connection to the revived ecosystem. Utilizing ecological data and understanding each degraded ecosystem's needs are crucial for effective restoration. This approach ensures the right species are planted in the right places, and those restoration efforts are tailored to the unique challenges of each site. Third, a holistic perspective addressing the underlying causes of environmental damage, such as unsustainable land-use practices or pollution, is essential for the long-term success of restoration efforts. Finally, innovation and adaptation by embracing new technologies and approaches can accelerate and enhance restoration processes. For example, drone-based seed dispersal holds promise for reforesting large areas efficiently [45].

3.4.3 Science-based decision-making

Science-based decision-making in forest management is a data-driven approach that utilizes sound scientific principles and evidence to inform forest management decisions. This management involves gathering and analyzing relevant data, utilizing scientific models and tools, engaging stakeholders, and monitoring and adapting. Gathering and analyzing relevant data include ecological data such as species composition, forest health, and soil quality, as well as socioeconomic data on local communities and forest-based industries. Utilizing scientific models and tools such as advanced models and simulations can predict the ecological and economic consequences of different management decisions, allowing for informed choices. Engaging stakeholders by consulting with experts, local communities, and forest workers ensures all perspectives are considered and fosters broader decision support. Monitoring and adapting by regularly monitoring the outcomes of implemented decisions and adapting management practices based on new data and changing circumstances is essential for continuous improvement.

Considering decisions' long-term ecological and economic implications, this approach promotes sustainable practices that safeguard biodiversity and forest health for future generations. Data-driven decisions minimize negative impacts on ecosystems, such as soil erosion, water pollution, and habitat loss. Informed decision-making optimizes timber production, carbon sequestration, and other ecosystem services, contributing to a thriving forest-based economy. Publicly available data and open communication with stakeholders build trust and transparency in forest management practices. Examples of science-based decision-making are precision forestry (i.e., GIS, remote sensing, and precision data collection techniques that allow for targeted forest management interventions, optimizing resource utilization, and minimizing environmental impact).

3.4.4 Challenges and opportunities

Thailand's journey toward sustainable forest management demands a multifaceted approach. Here are four key hurdles in balancing conservation with human needs: (1) balancing conservation needs with communities' livelihoods near or within protected areas, (2) addressing illegal logging, poaching, and encroachment effectively, (3) securing adequate funding and resources for long-term protected area management, and (4) raising awareness and public support for protected area expansion and sustainable forest management practices. By implementing these strategies and addressing the challenges, Thailand can continue to expand its protected areas and ensure the long-term health and resilience of its diverse and irreplaceable ecosystems. Remember, a healthy future for Thailand's forests goes hand-in-hand with a thriving future for its people and wildlife.

4. Conclusions

Protected areas provide sustainability of natural ecosystems and support species diversity. There is a huge interest in how large the PAs should be to be able to conserve diverse fauna and flora. In this study, the PA size was negatively associated with habitat fragmentation. Large PAs of 1600 km^2 or larger are preferred over small PAs to reduce habitat fragmentation due to agricultural land expansion and contribute to biodiversity conservation. Thailand is now in a concerning situation as there are 128 small PAs out of 180 PAs. Maintaining these small-size PAs and slowing down habitat fragmentation rates would be a significant challenge for Thailand to tackle.

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Conflict of interest

The authors declare no conflict of interest.

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Section 3

Climate Change and Forest Management

Chapter 6

Forests at the Crossroads: Biodiversity Conservation in the Era of Climate Change

Emad H.E. Yasin, Ahmed A.H. Siddig and Czimber Kornel

Abstract

Tropical forests are biodiversity-rich habitats on the globe because they host diversified flora and fauna species, provide a plethora of ecosystem goods and services to local communities, and sustain numerous ecological functions. The forest resources in Sudan are a vital aspect of the nation's ecological and economic framework. However, they face threats from agriculture, logging, and degradation, leading to loss of forest cover and reduced biodiversity. This chapter reviews Sudan's dryland forests, highlighting their importance, forest biodiversity, ecosystem services, environmental degradation, conservation challenges, biodiversity information gap, threats, and the urgent need for sustainable management strategies. It emphasizes the significance of protecting these forests to maintain ecological balance and promote socioeconomic development. Addressing these challenges requires urgent and effective conservation and management efforts to preserve these vital resources.

Keywords: forest biodiversity, ecosystem services, environmental degradation, conservation challenges, biodiversity information gap, threats, biodiversity conservation strategies

1. Introduction

Tropical forests contribute ecosystem services such as providing wildlife habitat, safeguarding against erosion and desertification, contributing to soil fertility, and many others [1]. Distribution patterns of plant species composition and diversity in natural habitats are issues of global interest today because environmental and anthropogenic factors greatly influence them. Forests in Sudan hold significant ecological, economic, and cultural value. They contribute to biodiversity, housing a variety of flora and fauna, and play a critical role in climate regulation. Economically, they support local and national economies through timber, medicinal resources, and tourism. Culturally, they are embedded in the country's heritage and traditions. However, Sudan's forests face considerable deforestation challenges. Approximately 28.4% of Sudan, or about 67,546,000 hectares, is forested. The primary drivers of deforestation include the conversion of natural forests to cropland and pasture, which significantly influences the country's deforestation rates. Additionally, fuelwood harvesting, constituting up to 80% of the national energy supply, has been a major cause of forest degradation [2].

Furthermore, Eltohami et al. [3] stated that the distribution of these resources is unbalanced (i.e., the greatest amount of the remaining forests is distributed in the south, whereas the poor and sparse woody formations characterize the northern part of Sudan where more people are concentrated and the need for forest goods and services is highest.) The areas free from human occupation such as reserved forests and national parks continue to represent habitats for an array of native flora. Maintaining reserved areas of natural vegetation within the human-dominated landscape is the only way to conserve native flora [4–7]. Therefore, habitat level analysis of vegetation becomes a vital for assessing the availability of plant resources, patterns of species diversity, and identification of botanical hot spots [8]. Conservation of biodiversity is crucial in a country, such as Sudan, where ecosystems are fragile, and renewable natural resources are endangered through over-exploitation. Ecosystems are rapidly deteriorating, primarily due to socioeconomic factors. Key contributors include agricultural expansion, logging, increased demand for livestock products, and urban development, particularly the construction of new transportation infrastructures. Additionally, economic and social pressures such as poverty and population growth are leading to harmful practices such as overgrazing, widespread tree cutting, soil erosion, desertification, overhunting, and overall land degradation. This environmental decline has led to the disappearance or severe endangerment of many aquatic and terrestrial species as their natural habitats are destroyed [2, 9].

Quantitative knowledge about basic stand diversity and structure and stand health indicators, such as canopy health and density of dead standing trees, are required for these current efforts toward attaining proper management and use of gum arabic-producing trees stands to be successful. Sudan faces a significant challenge in the management of its gum arabic-producing tree stands, primarily due to the absence of regular and long-term monitoring programs. This lack of systematic monitoring hinders the ability to track vital forest condition indicators in these areas. Despite the economic and ecological importance of gum arabic production, the country struggles to maintain a comprehensive understanding of the health and productivity of these forests. This situation is exacerbated by environmental stressors, such as climate change, which further affect these vital ecosystems. As a result, there is a pressing need for the establishment of robust monitoring systems to ensure sustainable management and conservation of Sudan's gum arabic-producing forest [3, 9–13]. Consequently, management and conservation planning are based on rough estimates. Baillie et al. [14] stated that to create effective forest management plans, it is obligatory to know which species present, consequently, management and conservation planning are based on rough estimates. Baillie et al. [14] stated that in order to create effective forest management plans, it is obligatory to know which species are present, their relative abundance and species-specific stages, and what factors control their future persistence and dynamics. Therefore, information about the current condition of natural reserved forests, including species composition, diversity, density, stage structure, and species-rich communities, are of primary importance in the planning and implementation of biodiversity conservation efforts [15].

2. Forest resources extent

Sudan's forests extend across several agroecological zones, which imply the existence of a variety of fauna and flora species that contribute directly or indirectly to the sustainable livelihood of local communities. In the period from 1980 to 1999, areas covered with forests in Sudan were estimated to be about 44 million acres, i.e., about 61% of the total

area of forests in arable lands, which equals about 73 million acres. In the mid-fifties, forests in Sudan constituted about 36% of the total area [16]. The forest resources in Sudan were estimated by FAO in 1990 to be about 19% of the total area of the country.

The national forest inventory, which was conducted by the Forest National Corporation (FNC) with the cooperation of FAO in 1995, documented that the forest cover was 24.9% of the total area of Sudan [17]. Sudan is classified as a moderately forested country with about 28% (67 million ha) forest and woodlands cover [18]. The scarcity of forest resources in Sudan is further aggravated by a high deforestation rate. FAO [19] ranked Sudan as the third country following Brazil and Indonesia in terms of net forest loss per year between 2000 and 2005. Deforestation in Sudan is attributed to many factors such as agricultural expansion, fires, overgrazing, and illicit felling of trees for fuelwood [20].

Forest resources in Sudan are inversely proportional to population density, 68% of Sudan's forests are in the south where 15% of the population live, and only 32% of the forests in the northern states in Sudan where 85% of the population lives [21]. In the year, 2005 forest resources were globally estimated and, accordingly, Sudan's forest cover found to be about 74 billion acres, which is equivalent to 29% of the area of the country. Nevertheless, there is an annual loss of these resources estimated to be about 589,000 acres. Yet, the global enumeration of forest resources, (2010), carried out by [22] in cooperation with different countries, presented a new profile for forest resource of Sudan. When completed in 2009, initial results of this assessment, noted that forest resources have dwindled from 74 million acres in the year 2005 to 69.949 million acres. Regrettably, this retraction of forest resources made the ratio of forest cover diminish from 29.6% in the year 2005 to 29.4% by late 2009 [23]. Based on the Afro-cover assessment and displayed in the NBSAP of 2015, the forest cover accounts for only 11.9% of the country's area with an annual deforestation rate exceeding 2.4%. Recent estimate based on FNC [24] report show that the forest cover occupies only 21.16% of total area of the country.

3. Forest diversity

The natural cover of Sudan is generally poor, sparse, and scanty vegetation due to its location in such arid environment of the country; except along the Nile banks and water courses where ephemeral herbs and grasses occur after the short rainy seasons. The reserved forests are about 837 forests distributed all over the country and occupy 85.90 million ha. This area represents 34.5% of the total land area of the country. These reserved forests are crucial for biodiversity conservation. They serve as vital habitats for a wide range of species, helping to preserve the ecological balance and biodiversity [25–27]. They constitute a great potential for biodiversity conservation and play vital role as an important component of natural resources and land use. Based on experts' opinions, these forests, including woodland savanna, are thought to be a home for over 500 unique species of trees and 185 species of shrubs, but this information have not been verified yet through field surveys [17, 28]. Al-Amin [29] is one of the prominent trees dendrology studies in Sudan has broadly classified the forest composition into three regions/ecosystems: (i) Arid and semiarid region (includes Northern, River Nile, Khartoum, White Nile, North Kordofan, North and West Darfur, and Red Sea states) where the vegetation is typical includes some scattered perennial vegetation, bushes and woody succulent thorny or leafless shrubs, and dominated by *Acacia tortilis, Capparis deciduas*, and *Maerua crassifollia* association. (ii) Dry Savanna ecosystem (includes Kassala, Gadaref, West Kordofan, and East and Central Darfur states) in which species richness

and stem density increase with noticeable abundance and dominance for species such as *Acacia seyal, Balanites aegyptiaca, Faidherbia albida, Ziziphus spina-chirsti,* and *Calotropis procera*. (iii) Wet Savanna ecosystem (Blue Nile, South Kordofan, and the South Darfur States) is essentially different and considered the richest and most dense region in Sudan in terms of trees and shrubs composition and diversity. Among the famous trees species occur at this zone are *Adansonia digitata, Balanites aegyptiaca, Borassus aethiopium, Cordia africana, Diospyros mespiliformis, Tamarindus indica, Prosopis africana, Sclerocarya birrea, Terminalia brownie, Crateva adansonii*, and *Comberetum* sp. In the basin and along the banks of the Nile and tributaries species, such as *Phoenix dactylifera*, *Acacia nilotica*, and *Tamarix aphylla*, are found.

4. Current status of biodiversity

4.1 Main ecosystems

Sudan's ecosystems are primarily categorized into two distinct types: aquatic and terrestrial ecosystems. Subsequent sections will provide detailed insights into both these ecosystems and their specific occurrences within the nation [30].

4.1.1 Aquatic (marine and freshwater) ecosystems

Contrary to its predominantly arid reputation, Sudan boasts a wealth of wetland ecosystems teeming with biological diversity and intriguing life forms. Notably, the eastern coast along the Red Sea harbors marine ecosystems characterized by lush mangrove forests and includes three protected marine areas, such as Senganeeb and Donganab. Additionally, Sudan is home to numerous inland freshwater habitats, including the river Nile and its tributaries, as well as various seasonal rivers, such as the Gash and Baraka, which originate in the Ethiopian highlands and create two inland deltas within the country. Furthermore, the nation is dotted with hundreds of lakes and ponds of varying sizes, each hosting a rich array of biodiversity [30].

4.1.2 Terrestrial ecosystems

4.1.2.1 Forests, grasslands, and mountains

According to Abdel Magid and Badi [31], Sudan's ecological landscape is categorized into five distinct vegetation zones, arranged from north to south based on rainfall patterns. They are: (i) desert, receiving 0–75 mm of precipitation, (ii) semidesert, with 75–300 mm, (iii) low rainfall savannah on clay and sand, with 300–800 mm, (iv) high rainfall savannah, receiving 800–1500 mm, and (v) mountain vegetation, ranging between 300 and 1000 mm of rainfall. These zones stretch from the arid desert in the far north to the lush savannahs (**Figure 1**). As per the recent land cover Atlas of Sudan, forests and rangelands together constitute 35.6% of Sudan's total land area [2, 28].

4.1.2.2 Agroecological zones

The agricultural sector is pivotal for Sudan's food security, enhancing food production, and offering employment in rural areas. Sudan has about 86 million hectares

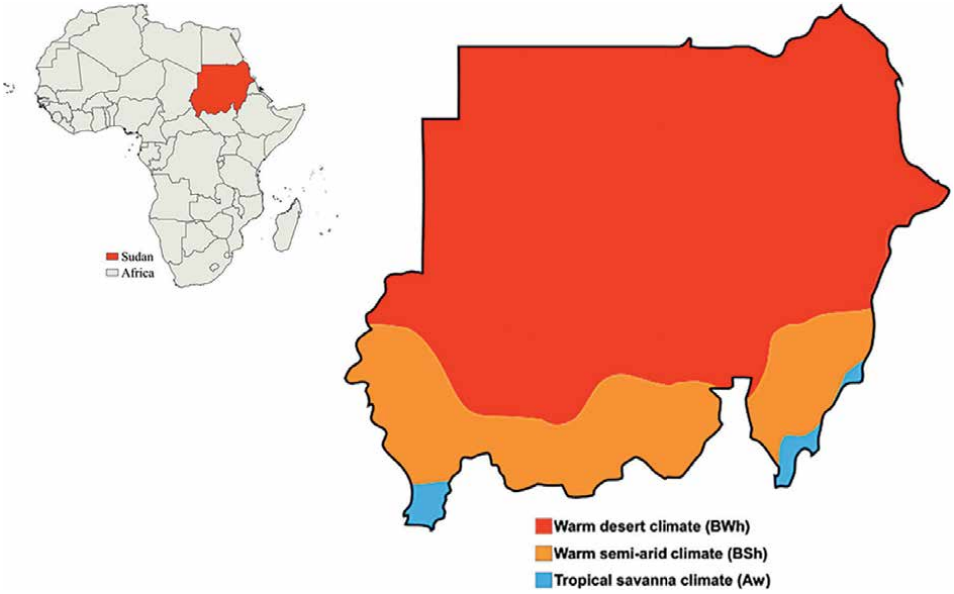


Figure 1.
Map of climatic zones of Sudan based on Köppen climate classification [30].

of cultivable land, yet less than 20% is utilized across three main farming subsectors. The irrigated sector, encompassing around one million hectares, contributes 21% to agricultural production value, including all wheat and a quarter of the country's sorghum. Despite its lower relative contribution to sorghum production compared to the rain-fed subsector, it offers stable output, especially critical during droughts for meeting consumption needs. The semi-mechanized rain-fed sector covers around 6 million hectares, primarily yielding sorghum and sesame, with crop success heavily reliant on rainfall. Additionally, the traditional rain-fed agropastoral sector spans about 9 million hectares in western, central, and southern Sudan, producing crops such as sorghum, millet, groundnuts, sesame, short-staple cotton, and gum Arabic.

Sudan's ecological zones, influenced by rainfall trends from north to south, dictate the distribution of its forests, transitioning from sparse bushland and shrubs in the arid north to dense, mixed forests in the southern savannah and mountain regions. The Nile basin cuts through Sudan from south to north, serving as a crucial water resource for agriculture, livestock, and forests. Forests and woodlands cover approximately 64.36 million hectares, while rangelands, providing 55–80% of the national herd's feed, span around 24 million hectares [27]. Livestock rearing is a significant livelihood for about 40% of the population, serving as a food source, wealth reserve, and a means of societal influence, particularly in areas underserved by banking and market systems (**Figure 2**) [2].

5. Socio-ecological services of forests

5.1 Ecological services of forests

The services provided by forests cover a wide range of ecological, economic, social, and cultural considerations and processes. Hence, ecosystem services are the

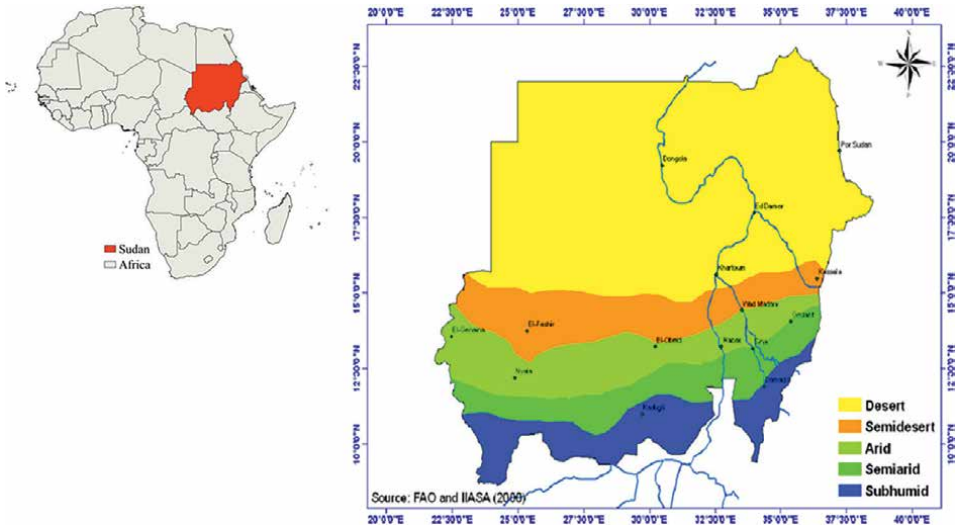


Figure 2.
Agroecological zones of the Sudan.

outcome of ecosystem functions that benefit human beings [32]. There are numerous services that forests provide in addition to their values of basic goods. They contribute more than other terrestrial biomass to climate-relevant cycles and biodiversity-related processes. As stated by Dail [33], the major services provided by forests include regulation of water regimes, modulating climate, maintenance of soil quality, carbon sequestration, maintenance of biodiversity in themselves, and being a habitat for other species, biological control, cultural, aesthetic, and amenity services.

5.2 Socioeconomic services of forest

Forests, as a renewable natural resource, have a significant role to play in assuring present and future food security by improving both the economic and physical well-being of both rural and urban people. The significant role of non-timber forest products (NTFPs) in supporting rural economies is evident in various countries with notable differences in their contributions to household income. In Sudan, NTFPs contribute over 50% to the cash income of rural households, a higher percentage compared to other countries. For instance, in Cameroon, the contribution is 39% [34, 35], while in Tunisia, NTFPs account for only 0.33% of the agricultural gross domestic product but contribute significantly, 32.30%, to the income of local forest populations [35, 36]. In Iran, NTFPs make up 21% of rural income [37], and in northern Thailand, they contribute 6.35% to community income [38]. Additionally, the importance of NTFPs extends to providing edible fruits to rural populations and the use of trees in traditional medicine [12, 39]. The importance of forests is indisputable, especially in developing countries. For instance, these woody species are considered an important source of energy for providing a substantial supply of firewood and charcoal to the local communities, as well as people in urban areas [40]. National energy surveys indicated that forests contribute 70.8% of the country national energy balance (4.01 million tons of oil equivalents) [41]. Sudan's forests provide a variety of goods, including timber in round and sawn forms, arboreal biomass for domestic energy supplies and building materials, and great varieties of non-wood forest products (NWFPs),

which are consumed for a variety of uses and traded locally or exported for external markets to get hard currency [42]. The most important role played by forest in Sudan's' rural areas is food security and the creation of job opportunities outside the agricultural season.

The production of honey and wax, in addition to game hunting and gum collection, are complementary and seasonal activities. During the periods of drought that stroked the Sahel, the fruits of some tree species were used extensively by local people as famine foods. Rangeland resources, particularly forests, contribute substantially to the income and subsistence of a large sector of the population who are either pastoralists or agropastoralists. It supplies about 80% of total feed requirement of the national herd and provides habitats for wildlife as well [43, 44]. Moreover, forests' inhabitant wild animals exert a significant influence on food production systems and ecological systems.

In addition, forestry activities provide significant opportunities for employment and income generation in almost all rural areas of Sudan. It was estimated that one out of seven of the population is engaged in forest-related activities [45]. Prehistoric people got their food mainly by hunting and gathering wild plants. Many of these people lived in the forest and were a natural part of it. With current urban expansion, people settled in cities, but they still went to the forests to get timber and to hunt. Also, forests provide a wide range of ecosystem services. For example, they protect soils from erosion, regulate the water regime; capture and store carbon, produce oxygen; , provide freshwater and habitat, help to reduce fire risk (in the tropics), and produce wood and non-wood forest products [46, 47]. In fact, forest resources became of high importance to communities not only for their great environmental services but also for the provision of livelihoods.

6. The value of plant diversity

Various plant species have diverse uses based on the socioeconomic context of a community. Natural forests are crucial for providing non-timber forest products (NTFPs) such as fruits, fodder, honey, and medicinal herbs. They are also key sources of tools, construction materials, timber, and food for local communities. Forests are home to numerous animal species, including those unique to Sudan. Most woody species are economically valuable, leading to their unsustainable utilization. Particularly, the overuse of certain species for timber and fuelwood has endangered them. Consequently, awareness of sustainable forest management is limited in local communities.

Notably, forests are vital for the majority of rural inhabitants, particularly those living near them. These people depend on forests for food, fodder, fiber, medicines, and income from selling collected items [48]. However, forests serve broader purposes than just producing wood and non-wood products. NTFPs are essential for global sustainable development [49]. They provide solutions for poverty eradication, environmental sustainability, food security, agriculture, energy, clean water, watershed protection, biodiversity preservation, climate change mitigation and adaptation, combating desertification and land degradation, and disaster risk reduction [49].

Forest-derived medicine is the primary healthcare source for 80% of the population in developing countries [49]. Forests are crucial for developing green economies and industries and offer indirect yet reliable resources for sustaining rural livelihoods, particularly for vulnerable groups, such as women and indigenous tribes. Forests also

Use	Trees species
Timber and building materials	*Acacia nilotica*, *Albizia aylemeri*, *Ailanthus excelsa*, *Balanites aegyptiaca*, *Borassus aethiopium*, *Burkea africana*, *Cassia siamea*, *Celtis integrofolia*, *Cordia africana*, *Crateva adansonii*, *Dalbergia sissso*, *Dalbergia melanoxylon*, *Daniellia oliveri*, *Detarium microcarpum*, *Kigelia africana*
Antiques	*Dalbergia melanoxylon*
Fruits, oil, and honey bee production	*Acacia nioltica*, *Adansonia digitata*, *Balanites aegyptiaca*, *Borassus aethiopium*, *Cordia africana*, *Diospyros mespiliformis*, *Grewia tenax*, *Ficus sycamorus*, *Hyphaene thebaica*, *Gardenia lutea*, *Tamarindus indica*, *Prosopis africana*, *Sclerocarya birrea*, *Terminalia brownie*, *Moringa oleifera*, *Ximenia americana*
Medicinal uses	*Salvadora persica*, *Acacia polyacantha*, *Adansonia digitata*, *Cissus quadrangularis*, *Cordia sinensis*, *Crateva adansonii*, *Cymbogogon citratus*, *Tamarindus indica*, *Stereospermum kunthianum*, *Albizia anthelmintica*, *Faedharbia albida*, *Fagonia cretica*, *Grewia villosa*, *Hydnora abyssica*, *Psidum guajava*, *Sterculia setigera*
Gums	*Acacia senegal*, *Acacia seyal*, *Acacia polyacantha*, *Sterculia setigera*
Fodder	*Balanites aegyptiaca*, *Ficus sycamorus*, *Ziziphus spina-christi*, *Faedherbia albida*, *Acacia senegal*, *Acacia mellifera*, *Stereospermum kunthianum*, *Combretum aculeatum*, *Maerua crassifolia*, *Cadaba grandulosa*, *Bauhinia rufescens*

Table 1.
Common Sudanese trees species and their uses as described in the National Biodiversity Strategy Action Plan for 2015 [30].

directly contribute to food security. About 200 million people, including many indigenous people, rely directly on forests for their survival, and over 1.6 billion people globally depend on them for food, medicines, fuel, employment, and livelihoods [49]. See **Table 1**.

Forests harbor over 80% of the world's terrestrial biodiversity [48, 49]. They are vital sources of biodiversity, energy, water, livelihoods, and other ecosystem services essential for societal functioning [37]. Forested catchments provide most of the world is freshwater, critical for human survival and food production, in addition to supporting livelihoods [37]. Forests play a role in soil erosion prevention, soil moisture retention, desertification control, and flood protection. Resilient forests are key in combating and adapting to climate change. Although currently about 10% of global greenhouse gas emissions are attributed to deforestation, forests have the potential to absorb and store approximately one-tenth of the projected anthropogenic carbon emissions for the first half of this century in their biomass, soils, and products, making them the second largest carbon storehouse after the oceans [48, 49].

7. The threats to the conservation of forest resources

Forest resources in Sudan are under severe pressure because of inhabitants, the need for farmlands, and grazing lands. There is a severe and increasing fuelwood gap in the country, which leads to the depletion of the standing stock and hence, further degradation of the remaining forest stands [50].

Despite ongoing conservation initiatives and the establishment of new protected areas, Sudan continues to face a significant biodiversity crisis. The decline of plant and animal habitats is primarily attributed to a range of human and natural threats,

as highlighted in studies by [2, 44, 51–54]. Key human-induced disturbances include deforestation, habitat destruction, urbanization, excessive exploitation of flora and fauna, agricultural expansion, land clearance, forest fire, and pollution [1, 55]. The contribution of various factors to the biodiversity crisis is significant, each affecting ecosystems in unique ways:

- *Deforestation:* the removal of forests not only destroys habitats for myriad species but also disrupts entire ecosystems. Forests play a crucial role in absorbing carbon dioxide; thus, deforestation increases carbon emissions and accelerates climate change.

- *Habitat destruction*: this process, often driven by urban sprawl and industrial development, fragments and destroys the living spaces of many species, impeding their ability to survive and reproduce. The preservation of crucial habitats is key to safeguarding biodiversity.

- *Urbanization*: the expansion of cities and urban areas results in the conversion of natural habitats into developed land. This transformation often brings about pollution and alters local climates, posing additional stress to wildlife and plant populations.

- *Excessive exploitation of flora and fauna*: overharvesting for various human needs can decimate plant and animal populations, leading to extinction and disrupting the balance of ecosystems.

- *Agricultural expansion*: the transformation of forests and natural habitats into agricultural land leads to significant habitat loss. The use of chemicals, such as pesticides and fertilizers in agriculture, can pollute water sources and harm a broad range of species.

- *Land clearance*: similar to deforestation, clearing land for agriculture or development contributes to habitat destruction, soil erosion, and alterations in local water cycles.

- *Forest fires*: some ecosystems depend on periodic natural fires for regeneration. However, human-induced or exacerbated forest fires can be devastating, causing loss of habitats, reduction in biodiversity, and adding to greenhouse gas emissions.

- *Pollution*: various forms of pollution—air, water, soil—can have severe impacts on ecosystems. Pollutants can accumulate in the food chain, causing declines in species populations and affecting overall ecosystem health.

Each of these factors contributes to the biodiversity crisis by disrupting natural processes, destroying habitats, and directly threatening the survival of species. Efforts to mitigate these impacts are crucial for preserving biodiversity. In contrast, in regions such as Sudan, natural factors such as desertification, erosion, climatic changes (including droughts and floods), fires, and landslides also significantly affect biodiversity and protected areas. These natural challenges compound the pressures on ecosystems, making the conservation of biodiversity even more crucial.

Siddig [9] offers a detailed examination of the barriers to conserving biodiversity in Sudan, focusing on issues stemming from governance and political turmoil. The challenges identified are as follows:

1. Ongoing wars and conflicts have displaced thousands from their homes, forcing them to seek refuge in areas rich in biodiversity, including forests and protected zones. This movement has significantly contributed to the deterioration of ecosystems and a decline in plant and wildlife populations.

2. Inadequate management programs and insufficient budgets hinder the implementation of national biodiversity strategies.

3. Extreme weather patterns, including prolonged droughts and unpredictable rainfall, are becoming more common, affecting ecosystems, agriculture, and water resources.

4. Competition over limited natural resources, such as agricultural fields, rangelands, and water, often leads to conflicts among communities, further destabilizing the region and its ecosystems.

5. Slow enforcement of laws and regulations due to the inefficiency of institutional frameworks.

6. The absence of effective programs to raise public awareness about the significance of preserving biodiversity and encouraging community participation.

7. The presence of financial constraints, a shortage of necessary equipment, and a lack of opportunities for professional training in conservation practices.

8. A lack of comprehensive national plans for the integrated utilization of land and natural resources.

9. Inadequate facilities for proper environmental monitoring, research, and implementation of conservation strategies limit effective biodiversity preservation.

8. Impacts of climate change on biodiversity

Climate change is an acute peril to Earth and its life forms. Reports by the Intergovernmental Panel on Climate Change (IPCC) indicate that a continuous temperature rise of 0.2°C per decade could lead to an overall increase of 1.5°C above preindustrial levels between 2030 and 2052 [56]. Such increases are likely to exacerbate natural hazards worldwide, including droughts, floods, and extreme weather events, with more frequent and severe occurrences expected [57, 58]. In Sudan, for instance, projections suggest a substantial temperature increase by 2100, with summer temperatures rising by 1.5–3.0°C and winter temperatures by 1.1–2.1°C [59].

Precipitation patterns are also predicted to change significantly, with overall decreases in rainfall and greater variability—ranging from a 15% to 190% coefficient of variation (CV). These changes include shifts in rainfall up to 6mm and alterations in the duration and onset of the rainy season. Consequently, water scarcity is

expected to amplify, intensifying the risk of land degradation [58, 60, 61]. Such climatic shifts pose a profound risk to the biodiversity of Sudan's drylands, diminishing ecosystem productivity and leading to losses in species diversity, ecosystem functions, and vegetation variety [58, 62].

The impacts of climate change on biodiversity are profound and far-reaching, affecting ecosystems and species across the globe. As the climate continues to warm due to human activities, particularly the emission of greenhouse gases, natural habitats are altered, and the conditions necessary for survival and health of many species are being undermined. The intricate balance of biodiversity, which has been shaped over millions of years, is now being reshuffled in mere decades, leading to uncertain futures for many species and ecosystems.

Several effects of climate change on biodiversity have been documented. These include shifts in species distributions as organisms move to cooler areas or higher altitudes, changes in phenology such as altered timing of migration and reproduction, and direct impacts from extreme weather events such as cyclones, droughts, floods, and heatwaves. These changes not only affect individual species but also the interactions between species, which can alter food webs and ecosystem functioning. For instance, Shivanna [63] reviewed 519 studies on ecological responses to extreme climate events, covering a wide range of taxa including amphibians, birds, fish, invertebrates, mammals, reptiles, and plants, illustrating the broad scope of climate impacts on biodiversity.

Furthermore, climate-induced impacts on ecosystems and biodiversity affect the availability of nature's beneficial services to society. Ecosystem services, such as pollination, water purification, and disease regulation, are vital for human well-being, and their disruption can have cascading effects on food security, health, and economies. Understanding these linkages is crucial for developing strategies to adapt to changing conditions and mitigate further damage [64].

Projections of the effects of climate change on biodiversity typically involve estimating changes for a single future time point, often failing to capture the dynamic nature of ecological responses. This underscores the need for more nuanced and long-term studies that can provide a clearer picture of how climate change will reshape the natural world. Such knowledge is essential for conservation efforts and for predicting how ecosystems will function in the future [65]. See **Figure 3**.

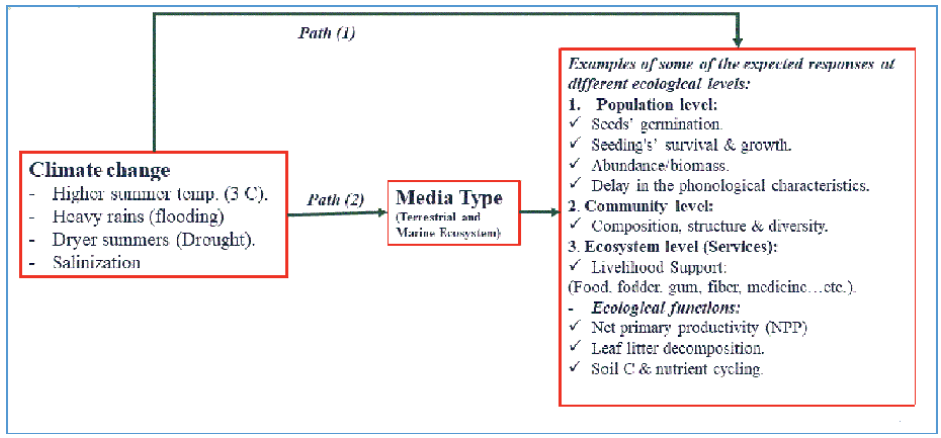


Figure 3.
Potential paths and responses for impact of climate change on biodiversity.

9. Understanding the deficit in biodiversity knowledge

Sudan's environment is predominantly harsh and dry, yet it is purported to host a rich array of plant, animal, and microbial life vital for the livelihoods of its inhabitants. This richness, largely based on expert knowledge or regional estimates, lacks substantiation from in-depth and policy-driven field research. Consequently, detailed information on the status and trends of these organisms and their environments is significantly lacking [9, 53]. Consensus among local conservationists and scientists points to a steady decline in biodiversity due to ongoing human pressure, conflict, governmental neglect, and the impacts of drought and desertification.

Additionally, Sudan faces challenges in gathering and disseminating scientific data, especially concerning biodiversity. There is a marked deficit in electronically available details about the diversity, numbers, and distribution of various life forms, including plants, microbes, insects, amphibians, fish, and birds. This gap extends to understanding ecosystems and genetic diversity [10].

While there is some awareness of Sudan's forestry, agriculture, and certain animal populations, considerable gaps remain, particularly regarding microbes, arthropods, amphibians, and reptiles. Most protected areas, critical for conservation, are understudied, and knowledge about their current state and threats is scarce. Notably, over 80% of wildlife research is focused on Dinder National Park, neglecting other protected areas [30].

To address this, initiatives to create new protected areas, ratify international conventions, and devise national biodiversity strategies should incorporate comprehensive biodiversity monitoring and assessment programs. These programs are vital for deepening understanding, enhancing documentation, and fostering policy-driven conservation. However, their success hinges on foundational efforts such as strengthening institutions, building capacity, establishing long-term monitoring, embracing technology, raising awareness, and enforcing laws.

10. Urgent management interventions and future directions

According to [28], Sudan adopted the global 20 Aichi Biodiversity Targets as its national strategic objectives. The NBSAP's key elements include the biodiversity of plants, forests, ranges, domestic animals, wildlife, marine life, and inland waters, as well as aspects of biotechnology and biosafety. Tailored and achievable targets for each of these components were established in alignment with the global objectives. The resulting proposed actions stem directly from these specific targets. Sudan demonstrates a political resolve to prioritize the integration of biodiversity and ecosystem considerations into major developmental agendas. Various channels for this integration exist, including the National Constitution, and diverse policies, strategies, and legislation. See **Figure 4**.

The Proposed National Constitution, especially highlights the need to weave biodiversity and ecosystem management into sustainable development policies, encompassing areas such as macroeconomics, agricultural policies, and climate change responses. The strategies for managing and conserving biodiversity and ecosystems have been woven into the broader fabric of sustainable development planning [30]. Recommendations to further these efforts are subsequently identified:

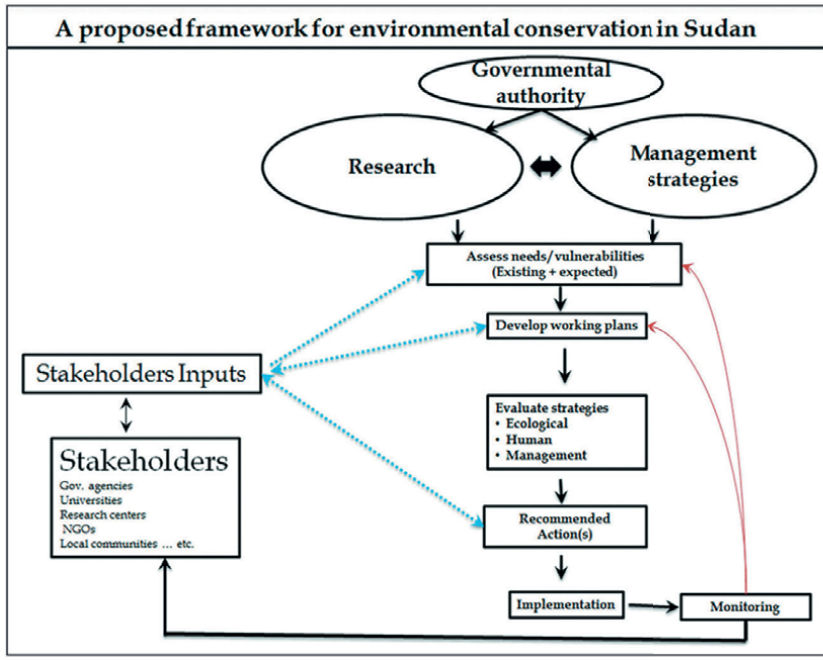


Figure 4.
A proposed framework for environmental conservation in Sudan based on the role of the government in initiating research and management plans with consideration of environmental stakeholders [9].

1. Conduct surveys and documentation of the current state of plant, wildlife, and microbial populations in Sudan to inform conservation decisions.

2. Prioritize attention to endangered species, those in need, and lesser-studied groups, such as microbes and amphibians.

3. Examine various ecosystems and agricultural zones, including those involving cultivated and natural plants, wild edibles, and weeds across different farming systems.

4. Create a national information system for sharing data on the status of biodiversity in both natural and controlled environments and consider integrating an early warning system.

5. Enhance the capacity of existing institutions in terms of coordination, staffing, and infrastructure.

6. Improve breeding capabilities within research and academic institutions to extend germplasm enhancement effectively.

7. Foster connections between the preservation and practical use of conserved genetic resources. Promote and support on-farm conservation for agricultural species.

8. Review and update the nation's strategies, policies, and laws concerning animal, forest, and agricultural sectors.

9. Empower rural communities by enhancing their ability to cooperatively manage natural resources, which will lead to improved forest and tree resource management.

10. Implement programs with local communities to safeguard forest resources, recognizing them as both impacted by and contributors to environmental change.

11. Apply sustainable practices for non-wood forest products (NWFP) through improved management, *in situ* conservation, agroforestry, legal reforms, conservation actions, reforestation, controlled grazing, energy-efficient household solutions, and community-based forest management. Utilize integrated land management to enhance agricultural stability and productivity.

12. Initiate national research initiatives to study and domesticate wild food varieties.

13. Establish in situ conservation sites for wild plant species, including crop wild relatives and native range plants.

14. Increase the number of protected areas to encompass over 17% of Sudan's land and ensure at least one protected area per state.

15. Ensure sustainable use of natural resources by indigenous and local communities.

16. Develop and implement robust systems and tools for monitoring, evaluating, and managing invasive alien species.

17. Future research should aim to understand the abundance and distribution of key indicator species and evaluate the impacts of human activity and climate change on ecosystems and these species.

18. Intensify research and data collection efforts on understudied aquatic ecosystems, focusing on freshwater and marine biodiversity, to fill existing knowledge gaps.

19. Establish partnerships with international conservation organizations to bring in expertise, resources, and global best practices for biodiversity management.

20. Develop and implement educational programs and campaigns to raise public awareness about the importance of biodiversity and the role individuals can play in its conservation.

21. Encourage community-led initiatives and participatory approaches in conservation projects to ensure that local knowledge and needs are integrated into biodiversity management.

22. Foster interdisciplinary research combining biological sciences with socioeconomic studies to understand the human impact on biodiversity and devise socioeconomically viable conservation strategies.

23. Promote ecotourism as a sustainable development strategy to generate revenue while preserving natural habitats and species.

24. Implement strict regulations and enforcement mechanisms to curb illegal activities such as poaching, logging, and unregulated fishing that threaten biodiversity.

25. Encourage the restoration of degraded habitats through reforestation, wetland restoration, and other rehabilitation projects to increase biodiversity and ecosystem resilience.

26. Monitor and address the impact of climate change on biodiversity by developing adaptive management strategies to help species and ecosystems cope with changing conditions.

27. Support genetic research and conservation to preserve the genetic diversity within species, crucial for their adaptability and survival.

11. Conclusion

Biodiversity and ecosystems provide crucial services to local communities. Often, policymakers focus only on the direct economic benefits of ecosystems, neglecting other significant values such as educational, social, and cultural aspects. This narrow view underestimates the ecosystems' true economic potential. Recognizing this potential is essential for the wise and effective use of ecosystem goods and services, considering their total economic value, which encompasses various functions and uses. The threats to biodiversity often stem from a limited understanding of its economic, cultural, spiritual, and social significance. For instance, South Sudan's secession led to a loss of diverse ecosystems, including forests, pastures, protected areas, and valuable wetlands. However, the remaining ecosystems still represent a rich biological diversity, forming a crucial part of the nation's heritage and assets. These ecosystems and biodiversity are under threat from multiple pressures and drivers. Agricultural expansion, at the expense of natural resources, has significantly impacted core resources such as forests, rangelands, and wildlife. Heavy land clearance machinery has caused widespread destruction of forests, resulting in large areas of bare land and loss of natural vegetation. This environmental degradation has led to a rapid decrease in forest biodiversity, including a reduction in the number and abundance of species across various ecosystems. Additional factors contributing to this degradation include traditional farming practices, human activities, overgrazing, drought, climate change impacts, land degradation, and the activities of the petroleum and gold mining industries. Conflicts, decentralization, and inadequate funding for conservation have also played a role. These issues have led to a decrease in forest and rangeland areas, forcing livestock to encroach on protected areas, leading to competition with wildlife for resources and disease transmission. Wildlife faces threats from poaching, becoming increasingly rare and endangered, exacerbated by the proliferation of arms due to civil conflicts and the resettlement of people around protected areas. The primary responsibility lies in conserving Sudan's natural heritage, including its ecosystems, species, and genetic diversity, while striving for sustainable benefits. Conservation efforts must prioritize the protection of biodiversity before considering its exploitation.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 7

Climate Change and Its Impact on Mountainous Plant Species: A Review

Patrush Lepcha

Abstract

Climate change poses unprecedented threats to ecosystems worldwide, and mountainous regions with rare ecosystems, unique landscapes, a large number of endemic species, and enormous plant biodiversity are highly sensitive to the effects of climate change. Early spring and late autumn events are major phenological changes observed in plants in response to climate change, and such changes mainly disturb the interaction between plants and their pollinators, thereby affecting the fitness and survival of both species. Climate warming is causing plant species to shift upward along the elevational gradient in the mountain, resulting in species accumulation at higher elevations and range contraction of several alpine plant species. Further, climate warming is augmenting the plant invasion by removing climatic barriers, thus threatening the diversity of native plant species. Moreover, climate warming is contributing to habitat fragmentation and loss and accelerating the associated impacts. All these impacts of climate change can potentially alter the composition, structure, and function of pristine mountain ecosystems, which leads to irreversible biodiversity losses. Thus, various climate change mitigation strategies, such as conventional mitigation strategies, negative emissions technologies, and radiative forcing or geoengineering technologies, are suggested to stabilize climate warming, thereby conserving irreversible global biodiversity loss.

Keywords: climate change, habitat fragmentation, habitat shift, mountain ecosystem, phenology, plant invasion

1. Introduction

Climate change refers to long-term alterations in local, regional, or global weather patterns (e.g., changes in temperature, precipitation, humidity, and atmospheric pressure) due to natural and anthropogenic activities. An increase in global air and oceanic temperature, the retreating of the global ice sheets, a rise in sea level, extreme weather events such as prolonged drought, frequent heat waves, erratic rainfall, an increase in flooding events, and the frequent occurrence of pests and diseases are the consequences of the climatic change evident at national and international levels. These events are posing unprecedented threats to the agroeconomy, the livelihood of marginal populations, global biodiversity, and

the structure, composition, and functions of various ecosystems across the globe. Climate change, therefore, has become a formidable intergovernmental challenge that impacts various domains of the environment, ecology, sociopolitics, and socioeconomy [1].

Mountains are unique ecosystems recognized for their complexity and diversity [2]. They harbor about 23% of the Earth's forests and 30% of all land, along with high levels of biodiversity and endemism [3]. Approximately 1/4th of the global human population inhabits mountainous regions across the globe, and many of them are poor [3]. Thus, the biodiversity of the mountains is pivotal for the sustainable development and survival of human societies [4]. Mountains possess the most distinct climatic gradients on earth and are one of the key "experimental fields of nature" because of the sharp environmental gradients they cover and the spatial fragmentation they generate at the otherwise global occurrence of habitat types and wilderness [5]. An average temperature decrease of −6°C is observed in mountains with every 1000 meters increase in elevation due to adiabatic lapse rate, and inversely, precipitation increases with increasing elevation because air masses cool and condense if it is elevated to higher elevations [6]. Thus, temperature and soil moisture are the major factors that determine the zonation of ecosystems along mountain gradients [5]. Such a type of zonation is the unique feature that differentiates mountain forests from other forests. The definition of mountain forest is obscure; however, a reasonable definition according to Price et al. [7] is "forests on land with an elevation of 2500 m above sea level or higher, irrespective of slope, or on land with an elevation of 300–2500 m and a slope with sharp changes in elevation within a short distance." However, mountain environments are highly sensitive to climate change [8, 9] and experience climate warming at a rapid pace compared to the Northern Hemisphere [10] or the lowlands [11]. Also, the future air temperatures of these regions are predicted to be higher than present-day temperatures [10, 12]. The macroclimate warming on mountains has accelerated the rate of species accumulation and potentially jeopardized the primary function of mountains, which is to act as long-term refugia for biodiversity [13].

Climate influences the vegetation patterns (structure, distribution, and ecology) of forests around the world [14]. Global warming of 1–2°C is sufficient to impact most landscapes and ecosystems by altering species composition, productivity, and biodiversity [15]. When environmental conditions alter, living organisms either escape, adapt, or become extinct [5]. In the case of plants, they mostly change their phenology [16] and shift their distributional range to higher latitudes and/or elevations [17, 18] to track climatic niches in response to climate change. Changes in flowering phenology often lead to plant-pollinator mismatches, which impact the reproduction, dispersal, fitness, and survival of the plants and associated pollinators and other species. The latitudinal or elevational shifts of plant species change the native species composition, increase the probability of the spread of alien invasive species (e.g., *Eupatorium, Lantana*, and *Parthenium* spp.) in the native ecosystems, and risk biodiversity. These events potentially accelerate competition among native and non-native plant species, which can lead to habitat fragmentation, biodiversity loss, and eventually the extinction of native flora. Therefore, this chapter delves into the influence of climate change on the phenology, habitat shifting, plant invasion, habitat fragmentation, and their consequences on native mountain biodiversity and ecosystems, along with the prospect of the preservation of mountain ecosystems and their unique plant diversity.

2. Climate change influencing plant phenology

Phenology is the study of the timing of various seasonal events in an organism's life cycle [19], including the response of organisms to climatic or seasonal changes (such as variation in temperature, precipitation, and duration of sunlight) in the environment in which they live [20]. Plants are adapted to the annual-seasonal cycle of a particular region, and seasonal atmospheric variations regulate the different stages of a plant's life cycle, such as the appearance of leaves and buds, first bloom or flowering, pollination, fertilization, seed dispersal, leaf senescence, and germination [20]. Temperature and photoperiod are the two major environmental factors that cause and control phenological patterns, especially in higher-latitude ecosystems [11–23]. The global climate warming phenomenon has drastically changed the various biological processes [24–26], including phenology [27, 28]. Thus, phenological events are sensitive and the most prominent indicators of climate change [29–32]. However, according to the study on Mediterranean shrubland and Mediterranean mountain forest, rainfall and water availability also affect plant phenology in addition to temperature [33]. Nonetheless, the early arrival of the growing season of vegetation, the early bud break, leaf flush or flowering during spring, and late leaf senescence and fruit maturation during autumn are the most widely studied impacts of climate change on plant phenology [34–37].

The climate warming in the Himalaya is higher than the average global temperature increase [38], and such warming immensely impacts the biodiversity in mountainous regions [39]. These regions are the "natural laboratory," which is ideal for studying the influence of climate change on floral phenology [40]. Variation in flowering phenology in response to climate change in mountainous regions has attracted many ecologists [40], and their studies have found that the mean flowering time of the mountain plant species is sensitive to temperature changes [41] as well as to changes in elevation, temperature, and precipitation along the elevation gradient of the mountains [42]. The temperate plant species in the Himalaya showed a mean phenological advancement of 1.9 days in spring events and a mean delay of 1.4 in autumn events per decade, and the average growing season length was extended by 3.3 days per decade [43]. Studies on flowering phenology in temperate mountains (e.g., the Alps) also indicated that spring phenology has preponded over the last few decades [44–46], and spring flowering times became earlier in the southern subtropical Nanling region of southern China in response to climate warming [47]. Field-based observations in the Himalaya showed that some species of *Rhododendron* are flowering a month earlier than in the past [48]. A similar result of 15 days early flowering in *Rhododendron arboreum* Smith compared to previous reports was observed in Kumaun Region of Central Himalaya (India) [49]. These shifts in peak flowering dates in *R. arboretum* over the past 100 years were due to the elevated seasonal and annual average maximum temperatures [50]. The mean flowering time in *Rhododendron* spp. advances 2.27 days per 1°C rise in mean annual temperature [41]. Periodic leafing and bud break in trees in the Himalayan forests has also advanced by 0.20 days per year for the past 30 years, and these changes are related to an increase in atmospheric temperature at the rate of 0.038°C per year [51].

The phenological responses of various plant species to climate change can cause asynchronous ecological interactions that threaten the structure and function of the ecosystem [52, 53]. Early and late flowering of the plants impact their ability to adapt to the surrounding environment, which determines the survival and death of the plant species [54]. Plant species can adapt to the changing environment if the changes

in their flowering phenology can track the rate of climate change; however, if the flowering phenological changes of the species cannot track the rate of climate change, such species cannot adapt and are eliminated [40]. Thus, the phenological alterations affect the demography, fitness, and survival of the plant species [55, 56]. Further, the survival of plant species depends on the reproductive success of pollinators [40]. Therefore, the risk of plant-pollinator mismatches increases with changing flowering phenology, which threatens the stability of the plant community and impacts ecosystem structure and functions [57]. For example, the changes in the timing of flowering of *Corydalis yanhusuo* W. T. Wang gave rise to a phenological mismatch with bumblebees (pollinators), which resulted in a low seed setting rate [58]. These observations indicate the inimical impact of climate warming on the phenology of plants [59, 60]. Thus, plant phenology is becoming an instrumental tool to monitor the effects of climate warming on vegetation shifts, which have detrimental impacts on biodiversity and ecosystem functioning [61, 62].

3. Climate change causing habitat shifts

Climate change is altering the environmental conditions of the habitats of plant and animal species, causing them to shift their habitat range in search of their climatic niche for survival [63]. Plant species either change elevational range or latitudinal range in response to climate change [64]. However, the tolerance level of individual species to environmental change determines the need for a shift and its extent [63]. It has been predicted that climate warming will shift the distributions of plants and animals toward the pole along the latitudinal gradient and toward higher elevation along the elevational gradient in the track of isotherms [65]. For example, a meta-analysis of more than 1700 plant species indicated that climate change is attributing to the advance of spring events by 2.3 days per decade and an average range shift of 6.1 m/decade toward the pole [17]. Several studies in the Alps indicated upslope elevational shifts of species in response to climate change, and they were able to track their ecological niche with rising global temperatures [66–69]. A study on changes in the optimum elevation of 171 forest plants between 1905–1985 and 1986–2005 indicated the upslope migration of plant species across six mountain ranges in France [66]. A study on Mt. Gongga (China) also depicted an upward shift of 53 plant species in response to climate change [70]. In the Nordic region (Northern Europe), the distribution of cereal and grass is likely to shift by up to 92.8 and 178.7 km, depending on the intensity of climate change [71], and some crop species have already been introduced to new areas [72]. Our study on large cardamom (*Amomum subulatum* Roxb., a commercially important spice crop of Sikkim, India) also indicated that cultivars previously grown at low elevations (below 975 m asl) are shifted to high elevations (above 975 m), and climate change is augmenting this elevational shift [73].

The plant diversity of the Alpine region in the mountain range is higher than the global average [74, 75]; thus, the Alpine meadows are included under the 200 critical global ecoregions [76]. However, plant species in the GLORIA (Global Observation Research Initiative in Alpine Environments) network of mountains in Europe have shifted their elevational distributions to higher elevations between 2001 and 2008, with an average shift of 2.7 m/year [77]. Telwala et al. [78] suggested that the winter temperature of alpine regions of Sikkim Himalaya (India) has become warmer than the winter temperature of the last two centuries, and the upper elevation limit of the species was shifted to 23–998 m with an average upward displacement rate of

27.5 ± 22.1 m per decade. About 87% of the 124 endemic plant species have shifted their geographic range in the region, which caused an increase in species richness in the upper alpine zone compared to the nineteenth century, and the plant assemblages and community structure of the region were substantially different compared to the last century [78]. The species richness of vascular plants on Mount Schrankogel, which is a major GLORIA site located in the Tyrolean Alps (Austria), increased by 11.8% within a decade [79]. Similarly, Parolo and Rossi [80] also reported that plant species richness in the Italian Alps was higher between the years 2003–2005 compared to 1954–1958. In addition to elevational shifts of mountain species [69], climate change can also cause contraction of the elevational ranges of mountain plants, which accelerates the threat of local extinctions of the endemic alpine species [80–84]. Such redistribution of plant species to new areas may alter the existing native plant communities and increase competition for space and nutrients for survival, which may disturb the prevalent structure and function of the mountain. Besides competition for resources and space, such exotic species expanding the elevational area and becoming invasive could disturb the functioning of the mountain ecosystem and increase the loss of mountain biodiversity [85, 86].

Along with the redistribution of native plants along mountain slopes, non-native plant species also tend to shift upward and expand their elevational range to colonize new habitats in the mountain ecosystem [87–90]. This habitat expansion or redistribution of non-native plant species toward the higher elevation of the mountain exerts an additional threat to native plants by increasing competition between them and non-native plant species at higher elevations [91]. Native and non-native species follow distinct patterns of distribution along the elevational gradients of the mountain because they have different ecological backgrounds and evolutionary histories [92, 93]. Thus, the direction and magnitude of elevational range shifts for native and non-native plant species differ significantly under changing macroclimates. However, several controversial results on species redistributions have also been reported in the past few decades, both at regional [66, 94] and global levels [95]. Apart from rising temperatures, changes in precipitation and the functional traits of plant species, such as their ability to disperse and colonize new areas, also contribute to the upward shift of species along an elevational gradient [70]. For example, studies in California [94] and the Mediterranean mountains of southern Europe [77] found that changes in precipitation patterns contributed more than temperature increases to the elevational shifts of plant species. Therefore, it is crucial to determine the major abiotic and biotic factors responsible for species redistribution. Nonetheless, the distinct macroclimatic gradients along the slope from the bottom of the valley to the top of the mountains act as a natural experimental field to investigate the effect of climate change on biodiversity [96, 97].

4. Climate change and plant invasion

Invasive plants are non-native plant species that are intentionally or inadvertently introduced into new geographic areas, eventually posing a threat to native plant diversity. Species with a broader physiological niche can tolerate a wide range of environments, and such species have a high potential to become invasive [98]. Biological invasions aided by climate change can exert extremely critical environmental impacts [99] and thus significantly contribute to environmental change across the globe [100]. Climate change intensifies the risks and losses in ecosystems through different mechanisms, including the removal of climatic barriers, thereby augmenting the spread of

invasive species [101, 102]. Compared to native plants, invasive plant species tend to shift their niche rapidly and are likely to adapt to new dwelling environments quickly [101, 103]. In addition, a rise in atmospheric carbon dioxide (CO_2) concentration and global warming favors the survival of invasive plant species over native plant species [104]. For example, the range of alien evergreen plants in Swiss forests has expanded in response to a decrease in the frequency of frost intervals due to climate warming [105]. Therefore, vegetation communities across the globe are expected to change because of the increases in global temperature [106].

Climate change has already elevated the spread of invasive species [107] and accelerated the expansion of native species [108], transforming them into invasive ones. For example, *Yushania maling* (Gamble) R.B. Majumdar & Karthik, which is native to the temperate zones of the Eastern Himalaya [109, 110], whose occurrence in Darjeeling district of West Bengal, India, was first recorded during the 1980s [111]. It has spread rapidly in the forest areas, potentially due to climate change causing a threat to the native floral diversity and ecosystems [109, 110, 112, 113]; thus, it is now considered a native invasive species in the region [109, 110, 113]. In mountain ecosystems, non-native invasive species are abundant between low and mid-elevations; however, anthropogenic activities and ongoing climate change are likely to accelerate their spread and dominance at high elevations [114]. Priyanka and Joshi [115] also suggested that most parts of the western and southern regions of the western Himalaya (India) tend to become suitable for the expansion of invasive pant *Lantana camara* L. in the future due to increased warming. In Kashmir (part of the western Himalaya), the invasive species are already augmenting the homogenization of the terrestrial ecosystems [116]. These invasive species are invading protected areas of the region and disturbing the habitat and food availability of the native wildlife [117, 118]. Such reports indicate that the mountainous regions are vulnerable to plant invasion due to climate change, specifically climate warming.

Invasive plant species are known to alter the diversity and composition of the native flora and form nearly mono-specific stands (homogenization). They also impact a wide range of abiotic and biotic factors that could potentially change the function and services contributed by the invaded ecosystems. Invasive plant species can directly impact the activity, productivity, and survival of native biota [119]. They have superior potential to compete for space and resources and a more efficient capacity to utilize resources than the native species. Thus, they have a major influence on resources (e.g., nutrients) and space in new habitats, as well as modify ecological processes, thereby outcompete native species and degrade the habitats of native biota in the ecosystems [120]. In brief, invasive plant species displace native plant species from their original habitats, degrade ecosystems, have a negative impact on human health [121, 122], homogenize the world's biological systems, and cause global biodiversity loss. Therefore, climate change-driven biological invasions could potentially disrupt the diversity, composition, structure, function, and services of mountain ecosystems and cause a severe impact on mountain biodiversity.

5. Habitat fragmentation and biodiversity loss due to climate change

Global biodiversity is under severe threat due to increasing anthropogenic activities (e.g., habitat destruction) and climate change. Habitat fragmentation or

habitat loss of plants is generally attributed to human-induced causes such as change in land-use patterns, deforestation, overexploitation, intentional forest fires, and pollution. However, climate change also causes fragmentation of favorable habitats, leading to a decline in the habitat quality of the species [123]. Habitat fragmentation produces small populations with widening spatial isolation, which potentially accelerates the risk of extinction [124–126]. Mantyka-Pringle [127] suggested that recent climate and climate change are key factors that determine the negative effects of habitat loss, and raising temperatures is the major determinant of habitat loss and fragmentation effects, while change in precipitation over the past 100 years is of secondary importance. Further, habitat loss and fragmentation effects were highest in regions with high maximum temperatures [127], suggesting that climate change is contributing to enhanced habitat fragmentation across the globe. In landscapes undergoing habitat fragmentation, certain species will obviously be affected by habitat loss, and in such a scenario, associated or dependent species may also be lost, causing populations to decline [128–130]. Nonetheless, there has been massive biodiversity loss over the past few decades that can potentially initiate the sixth mass extinction crisis due to the environmental changes induced by anthropogenic activities [131].

Climate change is considered a major factor in the decline of global biodiversity. At a basic level, climate change is influencing the reduction of genetic diversity in populations due to rapid migration and directional selection, which can further affect the resilience and functioning of the ecosystem [132]. At the community level, the "web of interactions" among different populations is likely to be modified due to the various effects of climate change [133, 134]. As described in the sections above, climate change alters phenological events, thereby disrupting plant-pollinator interactions [57]. This can cause the extinction of both pollinators and plants, with expected impacts on the structure of plant-pollinator networks [135, 136]. Based on the study of 9650 inter-specific systems, which include pollinators and parasites, about 6300 species are expected to disappear along with the extinction of their associated species [137]. Several climatic variables determine the geographical distribution ranges of various species, and therefore, species shift their distribution range depending upon their dispersal capacities and go locally extinct in response to climate change [138, 139]. Such redistribution of species reduces biodiversity at low elevations and latitudes and causes habitat fragmentation and range contraction of several native species in alpine and polar ecosystems, paving the way for their disappearance from the ecosystem. Further, a global rise in temperature favors the survival of invasive alien plant species over native plant species [106]. These invasive plant species are known to alter the environment they invade, have efficient dispersal and reproductive capacity, and thus outcompete the native plant species in terms of space and resource utilization. They homogenize the diversity and composition of the invaded region, resulting in the loss of native biodiversity. Most of the studies at present indicate that habitat loss and fragmentation have a greater impact on species and ecosystems than climate warming [140–143]. However, in due course, the effect of climate change is expected to increase and contribute more to determining population trends than habitat fragmentation and loss [144]. Based on this chapter, the consequences of climate change on mountainous plant species and the different ways in which climate change leads to biodiversity loss are summarized in **Figure 1**.

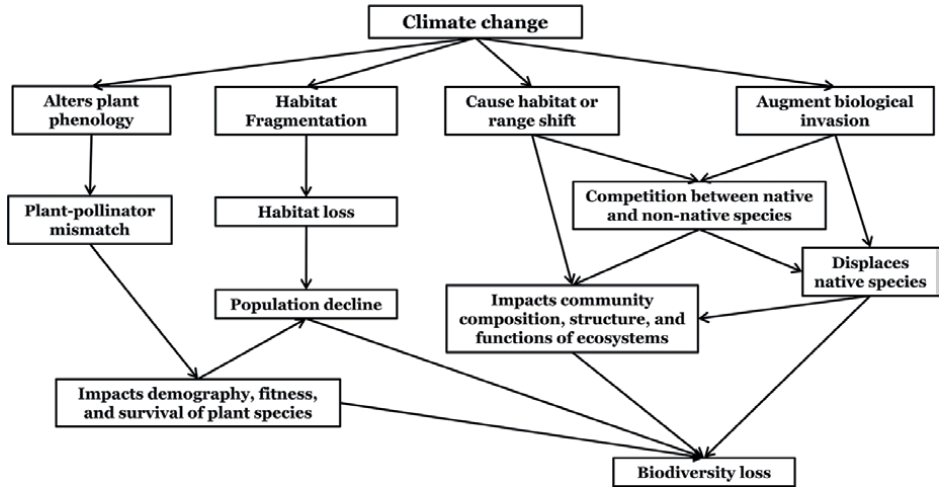


Figure 1.
Impact of climate change on mountainous plant species leading to biodiversity loss.

6. Climate change mitigation and future prospective

As of now, the discussion in this chapter has strongly indicated that climate warming is the major driver of climate change-related biological consequences like change in plant phenology, upward elevational shift, plant invasion, habitat fragmentation, and biodiversity loss. Therefore, global climate change mitigation strategies should focus primarily on minimizing or stabilizing the global temperature increase in order to regulate the biological issues that arise due to climate change. There is ample literature that provides knowledge about the initiation of global summits and conventions aimed at framing policies to regulate climate change and biodiversity loss. Therefore, this section directly focuses on the three widely discussed climate change mitigation strategies suggested recently by Fawzy et al. [145]:

Conventional mitigation strategies: energy-related emissions of various gases are the major driver for raising the concentration of atmospheric greenhouse gases. Therefore, conventional mitigation strategies prioritize the use of decarbonization technologies and techniques that decrease carbon dioxide (CO_2) emissions. Conventional mitigation strategies are deployed in four main sectors: on the supply side (power sector) and on the demand side (industry, buildings, and transportation sectors). Mitigation efforts on the supply side include decarbonization through the utilization of renewable energy, fuel switching to low-carbon fuels such as natural gas and renewable fuels, carbon capture and storage, and nuclear power. On the demand side, mitigation efforts include gaining efficiency through the utilization of sector-specific technologies; energy-efficient methods that reduce the consumption of energy; and the inclusion of renewable power technologies that are within the energy matrix of sectors on the demand side [146, 147]. Most of the conventional mitigation technologies are well established and have an acceptable level of managed risk.

Negative emissions technologies or carbon dioxide removal methods: include the techniques deployed to capture and sequester atmospheric CO_2 [148]. For example,

wetland construction and restoration, afforestation and reforestation, direct air carbon capture and storage, bioenergy carbon capture and storage, enhanced weathering, ocean alkalinity enhancement, soil carbon sequestration, etc. To date, afforestation and reforestation, as well as bioenergy carbon capture and storage, are included in the IPCC assessments [149]. However, a study suggested that negative emissions technologies are still in their infancy; therefore, climate policy should remain focused on conventional mitigation technologies, while further financial resources should be invested to accelerate the progress of negative emissions technologies [150].

Radiative forcing geoengineering technologies: focus on the reduction or stabilization of atmospheric temperature by altering the radiation balance of the earth through managing solar and terrestrial radiation. Unlike the above two strategies, this technique suggests stabilizing temperature without changing the concentration of greenhouse gases. For example: cirrus cloud thinning, marine sky brightening, stratospheric aerosol injection, space-based mirrors, surface-based brightening, etc. However, these strategies are still theoretical, in the early stages of trial, and uncertain and risky in terms of large-scale practical utilization. Therefore, radiative forcing geoengineering techniques are still not included in climate policy frameworks [151, 152].

7. Conclusion

Climate change is one of the major issues facing our planet in the anthropocene. Mountainous regions of the world harbor unique ecosystems and high biodiversity and are considered the refugia of biodiversity. However, these regions of the world are highly sensitive to climate change; therefore, the impact of climate change is highly visible on mountains as compared to lowlands. Climate warming, or an increase in the global earth's temperature, is the major climatic change that is impacting the entire world and the mountains in particular. The phenological changes, such as early spring events and late autumn events, are evidently disturbing the various plant-animal interactions, such as plant-pollinator interactions. Raising temperatures are compelling various plant species to shift their geographic ranges in search of suitable climatic niches. Climate warming is further removing climatic barriers for invasive alien plant species and increasing the possibilities of their invasions in new areas. Climate change, along with other anthropogenic activities, is contributing to major habitat fragmentation or loss for several plant species. All these responses of mountainous plants to climate change would alter the species composition, structure, and functioning of the mountain ecosystems, eventually leading to the extinction and biodiversity loss of native plant species. Therefore, it is pivotal to mitigate climate change in order to conserve the sixth biodiversity extinction because the economy and livelihood of people living on mountains directly or indirectly depend on the biodiversity and services provided by mountain ecosystems. The major focus of climate change mitigation should be reducing or stabilizing the global temperature because global warming is the major driver of most of the biological changes caused by climate change. Conventional mitigation strategies, negative emissions technologies, carbon dioxide removal methods, and radiative forcing geoengineering technologies are the major strategies that can be explored further for climate change mitigation.

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Chapter 8

Shifting Tides: Unraveling the Sociological Fabric of Climate Change

Anita Shrestha and Shyam Krishna Shrestha

Abstract

This study shifts its focus from the predominant biophysical perspective of climate change (CC) to a sociological lens, particularly in the context of the Ramechhap district, Nepal. It delves into the local perceptions of CC and emphasizes its sociological impact on livelihoods. Employing a constructivist theory and the complex human—environment systems, the research extensively explores institutional, structural, and societal pathways of adaptation. The study employs a qualitative data, utilizing purposive sampling and ethnographic methods such as observation, case studies, KIIs, and FGDs. The findings underscore the challenges faced by farmers in the Ramechhap, particularly those dependent on forest, agriculture and livestock, due to the impacts of global warming. Issues such as increased drought, temperature fluctuations, altered monsoons, and other climate-induced changes emerge as disruptive factors affecting the agricultural system, rendering it vulnerable and less productive. To counteract these climate risks, farmers in the Ramechhap employ adaptive measures grounded in traditional and local knowledge concurrently integrating new technologies. Adjustments to crop varieties based on climate disturbances and the establishment of collective networks and social relations through the exchange of experiences are crucial strategies. The research contributes valuable sociological insights into the local dynamics of CC and proposes holistic CC policies.

Keywords: Nepal, climate change, complex human-environment systems, sociological lens, livelihood

1. Introduction

In the relentless pursuit of unraveling the multifaceted implications of climate change (CC), this study pioneers a distinctive approach, shifting its gaze from the prevailing biophysical paradigm to a sociological lens. Nestled in the heart of this exploration is the Ramechhap district in Nepal, a locale where the research probes local perceptions of CC and meticulously underscores its sociological repercussions on livelihoods [1]. Inspired by constructivist theory [2] and the conceptual framework of complex human–environment systems (CHANS) [3], this study investigates the intricate pathways of adaptation, delving into the institutional, structural, and societal dimensions that define the human response to a changing environment.

Imbued with a qualitative essence, this research employs purposive sampling and ethnographic methods, such as observation, informal discussions, case studies, in-depth interviews, and group discussions [4]. The diversity of respondents enriches our comprehension of the local dynamics, echoing the sentiments of Patton [5]. A distinct facet of this study lies in its exploration of the symbiotic relationship between humans and the environment in the throes of CC, with a specific lens on communities reliant on forest, agriculture, and livestock.

Central to the narrative is the looming force of global warming, a pivotal factor profoundly impacting the lives of farmers in Ramechhap, thrusting them into a daily struggle. The research reveals increased drought, temperature fluctuations, altered monsoons, and other climate-induced disruptions that cast a shadow over the agricultural system, rendering it vulnerable and less productive [6]. In response to these challenges, the farmers in the region exhibit resilience by employing adaptive measures grounded in traditional wisdom, concurrently integrating new technologies and skills.

This research unfolds a tapestry of nuanced strategies employed by the community, ranging from adjusting crop varieties based on climate disturbances to fostering collective networks and social relations through the exchange of experiences [7]. Beyond providing profound sociological insights into the local dynamics of CC, this study contends that these findings can significantly contribute to the formulation of more holistic CC policies.

The reciprocal relationship between society and the environment is a dynamic interplay that significantly influences each other's development and sustenance [8]. Individuals' interactions with their surroundings are shaped by personal experiences and subjective meanings within the local context [9–12]. Simultaneously, society is intricately intertwined with and reliant upon the natural world, creating a continuous cycle of impact and influence. To comprehensively study society, sociology must acknowledge and explore its interconnectedness with the environment [8].

Environmental sociologists delve into the intricate relationship between humans and their natural surroundings, acknowledging the complexity and multifaceted nature of this connection [13]. Researchers emphasize that the social world is constructed through subjective experiences and the mundane activities of daily life [14, 15].

In contrast, Schaiberg [16] introduces the concept of societal-environmental dialectics, emphasizing that while environmental problems have an ontological status, their recognition as issues stems from social processes. Environmental problems must be understood through social processes, despite any external influences or inherent material bases. In this context, the researchers argue that the relationship between society and the environment in the Ramechhap encompasses a broad spectrum, with a specific focus on society's interaction with CC.

The study explores societal components and their interactions with the environment, specifically examining the effects of CC on farmers' livelihoods and their adaptation practices. Various theoretical frameworks serve as a foundation for understanding these themes. The perception, knowledge, experience, and responses to CC vary based on factors such as gender, class, age, status, ethnicity, education, occupation, and other forms of social experience and residence [17–22]. The researchers contend that these individual characteristics play a crucial role in shaping farmers' knowledge, experiences, and perceptions of CC through socialization processes and cooperative activities.

Most environmental research on CC has traditionally focused on natural and physical aspects, such as temperature, air, water, glaciers, global warming, and other ecological factors [23–25]. However, sociological research on the environment

emerged in the 1970s, with environmental sociology addressing the relationship between humans and their natural surroundings. Since the 1990s, CC research within the sociological perspective has gained momentum [8]. A workshop in 2008 marked a turning point, bringing together environmental sociologists to discuss CC research, emphasizing societal, structural, and cultural driving forces alongside the natural science community's analysis of CC drivers [26, 27].

As the chapters unfold, the narrative not only paints a nuanced picture of the challenges faced by the communities in Ramechhap but also accentuates the resilience and resourcefulness exhibited by farmers in adapting to the evolving climate. The methodological blueprint of this study stands as a guide for similar sociological investigations in regions grappling with comparable challenges, aiming to foster a broader understanding of the human dimensions of CC. Thus, the objective of this study is to delve into the sociological impacts of CC on farmers in the Ramechhap district, Nepal, particularly those dependent on forests, agriculture, and livestock, providing a comprehensive understanding of daily challenges and vulnerabilities.

1.1 Theoretical/conceptual framework

The foundation of this book chapter rests upon the coupled human and natural systems (CHANS) framework, which delves into the evolving relationship between humans and nature within the dynamic landscape of global sustainability [3, 28]. Considering the interconnectedness of social and natural sciences, the CHANS framework emerges as a preferred method for sociological research [8]. It underscores the intricate relationships between social, economic, political, and natural elements, offering a comprehensive perspective that extends beyond specific environmental agendas including CC.

Originating as a response to the imperative of integrating social sciences into global CC research, the CHANS framework is particularly suited for place-based studies. It examines the interactions between human activities and natural systems, emphasizing emergent behaviors resulting from adaptive actions [8]. Notably, the CHANS approach explicitly recognizes the mutual coupling of human and natural systems through reciprocal interactions involving material, energy, and information flows. The study of feedbacks, surprises, nonlinearities, thresholds, time lags, legacy effects, path dependence, and emergence becomes paramount in understanding these complex interactions [3].

The CHANS is a robust and timely framework for studying the interactions between human and natural systems [29]. This framework offers both theoretical foundations and practical methodologies to delve into the complex relationships between humans and their environments. Drawing from interdisciplinary fields like ecological anthropology and human ecology, CHANS science adopts a holistic viewpoint that encompasses the interconnected patterns and processes across different scales. This approach facilitates the examination of how human actions and natural processes influence each other, which is crucial for navigating the challenges of the Anthropocene era. By integrating various disciplines and acknowledging the mutual dependence of human and natural systems, CHANS science becomes pivotal in devising innovative solutions for the unprecedented global issues we confront (**Figure 1**).

In the realm of sociology focusing on human dimensions in CC, three main approaches exist: individual level analysis, the CHANS approach, and the post-political approach [8]. Developed as part of the global CC research program initiated by the International Social Science Council (ISSC) in 1996, the CHANS approach

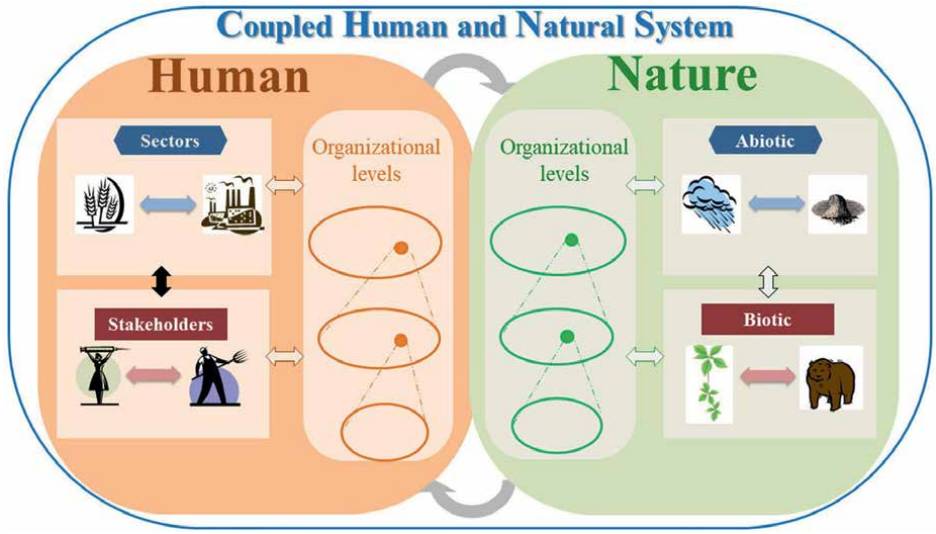


Figure 1.
Schematic diagram of a coupled human and natural system. Arrows show interactions and feedbacks. (Courtesy of Vanessa Hull.)

investigates embedded CC within social structures, institutions, cultural values, beliefs, and social practices [8]. It recognizes that the interactions between nature and society provide opportunities to observe both societal and environmental changes. Empirical investigations into CC perceptions and adaptation, particularly in the context of traditional rainfed farming in Ramechhap, reveal significant influences on farmers shaped by changes in the natural–physical environment.

The theoretical framework of this study is grounded in the eco-sociological concept, exploring interactions between CC and society, specifically in the context of Ramechhap, Nepal. This study considers fluctuations in rainfall, temperature, atmospheric moisture, and precipitation as events impacting social lives, adopting a multidisciplinary approach that integrates structural functionalism, organic roles, and hierarchical systems within socioculture to understand the consequences of environmental changes on residential areas.

The study focuses on the relationship between society and the environment, addressing how farmers in Ramechhap experience and adapt to climate disorders. Drawing on various sociological theories, including environmental sociology, symbolic interactionism, and constructivism, the researchers acknowledge the limitations of relying on a single theoretical perspective and advocate for a comparative method to better understand societal and environmental interactions in Ramechhap.

Additionally, the study incorporates insights from classical sociologists like Durkheim, Weber, and Marx, highlighting the mutual influence of nature and society. It discusses the application of the CHANS approach to comprehend the intervention of global politics and governmental strategies in managing environmental stresses for sustainable livelihood in undeveloped areas.

The conceptual framework visualizes the ways in which Ramechhap farmers interact with their environment, considering sociocultural, adaptive, natural–physical, and political–economic aspects. This framework demonstrates the interconnectivity of these factors in shaping the collective lives of the community, integrating perspectives from structural functionalism, constructivism, developmental approaches, and

CHANS to provide a comprehensive understanding of the complex dynamics between society and the environment in Ramechhap.

2. Methodology

This chapter illuminates the study area, the methodological framework employed in unraveling the local realities of CC, and adaptation strategies within the Ramechhap district of Nepal. The research design is characterized by a dual qualitative approach, incorporating both emic and etic perspectives, and draws upon an array of data sources, ethnographic sampling techniques, and analytical methods.

2.1 Study area

Nepal is located in South Asia. It is a landlocked country situated between India to the south, east, and west, and China to the north. The geographical coordinates place Nepal in the southern part of the Asian continent. The Ramechhap district in Nepal was chosen by researchers for specific reasons. First and foremost, the characteristics of the area align well with the research questions and variable relationships. Ramechhap faces high vulnerability to various environmental challenges such as glacial lake outburst flood (GLOF), floods, droughts, and landslides, being situated in the central development region of Nepal [30]. Additionally, as reported by the District Development Committee (DDC) in 2010, 18 Village Development Committees (VDCs) in the southern belt of Ramechhap consistently experience drought issues. Major land use of the district are forest, agriculture, settlement, infrastructures like hydropower, roads, government buildings, baren land, rivers and streams, and snow covered highland (**Figure 2**).

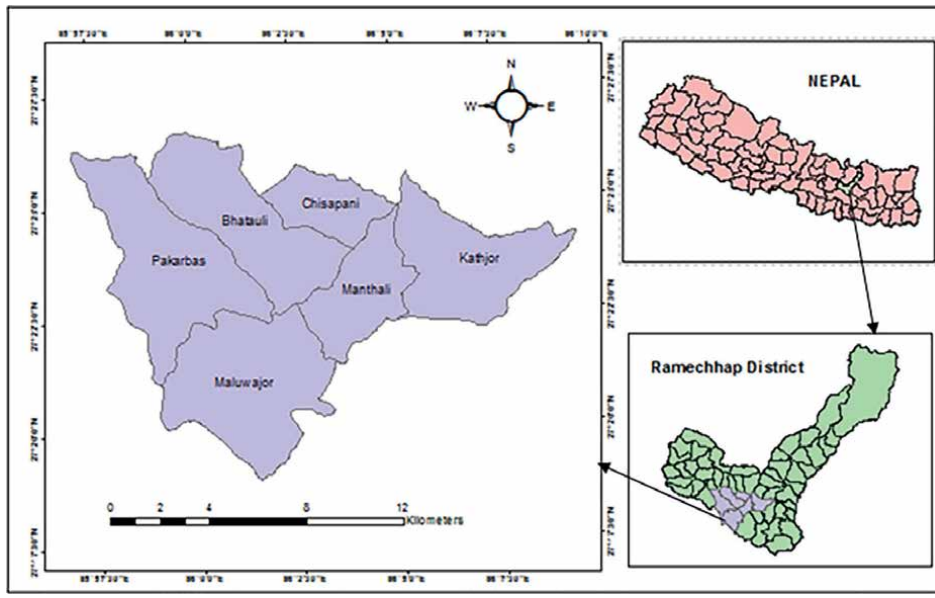


Figure 2.
Map of the study area.

2.2 Data sources

The secondary data for this research emanates from a rich tapestry of published and unpublished articles, journals, books, reports, and documents centered on CC policies, legislation, and directives. A meticulous review of policy documents, CC progress reports, guidelines, CC workshop proceedings, and documents from diverse organizations and individuals adds depth to the dataset.

2.3 Ethnographic sampling

The study employed a purposeful sampling strategy, intricately woven into the cultural fabric of the local populace in the study area. Key informants, carefully chosen within organizations, and individuals selected based on their interactions with villagers, recommendations, and knowledge pertinent to the research questions, form the cornerstone of the ethnographic sampling—snowball sampling technique.

2.4 Data collection techniques

The qualitative approach unfolds through a comprehensive arsenal of data collection techniques, including in-depth interviews, field observation, and focus group discussions. The emic approach probes into how local people perceive and think about the world, while the etic perspective shifts focus to scientific observations and interpretations. A dedicated 7 months and 8 days were spent in the field, entailing participatory observation and immersive field visits.

2.5 Field observations

Field observations serve as a crucial lens through which drought conditions, forest health, water scarcity, and agricultural challenges are unearthed. These on-the-ground insights provide a dynamic understanding of the environmental nuances faced by the community.

2.6 Focus group discussions (FGDs) and key informants' interviews (KIIs)

The researchers engaged in conducting FGDs and KIIs, unraveling local perceptions and practices related to CC. These qualitative interactions delve into the rich tapestry of community experiences, capturing diverse voices and perspectives.

2.7 Data analysis

The qualitative data undergoes a meticulous analysis employing content analysis, case studies, and thematic categorization. Field notes, maintained daily, serve as a reservoir of methodological, descriptive, and analytical insights, capturing the nuances of observations and interactions.

2.8 Triangulation

The methodological rigor is reinforced through triangulation, ensuring the validity and reliability of the data. Cross-checking information through various methods, sources, and perspectives provides a corroboration for the findings.

3. Climate change status of Nepal

Nepal characterized by diverse climates spanning tropical to alpine regions within a mere 200-kilometer range from south to north exhibits climatic variations at every elevation. The national mean temperature, excluding mountain valleys, centers around 15 degrees Celsius. Rainfall patterns increase progressively from west to east, averaging 1500 mm. In the face of rising temperatures and unpredictable precipitation, uncertainties escalate, emphasizing vulnerabilities and the imperative for adaptive measures. The discourse predominantly revolves around two categories of disasters: rapid-onset events like floods and landslides, and slower-onset occurrences such as droughts, forest fires, snowmelt, and regional sedimentation.

A climate trend analysis conducted by the Department of Hydrology and Meteorology (DHM) in 2017 [31] indicates a discernible rise in the annual maximum temperature at a rate of 0.056°C per year. Conversely, the trend in minimum temperature demonstrates a relatively insignificant increase of 0.002°C per year. Notably, certain mountainous regions, like Humla and Manang, experience a decline in minimum temperature, while the central Tarai region -Madhes Province and the Middle Mountainous region demonstrate an increase. The elevated maximum temperature consistently trends higher from east to west in mountainous districts, with the lowest levels observed in the Tarai districts. Furthermore, the mean annual precipitation in Nepal has undergone a reduction of 1.3 mm per year over the monitored interval from 1971 to 2014.

Between 1971 and 2019, Nepal recorded an annual average of 647 fatalities attributed to climate-induced disasters, constituting approximately 65 percent of all disaster-related deaths, excluding road accidents. The highest peak in casualties occurred in 2001. The annual economic loss averaged USD 21 million, equivalent to around 0.08 percent of the FY2018/19 GDP at current prices. The Tarai floods in 2017 resulted in the highest economic loss of USD 678 million, accounting for about 2.08 percent of the FY2017/18 GDP at current prices. Predominantly, Nepal's most impactful climate-induced disasters include floods, landslides, epidemics, and fires, with epidemics accounting for the highest mortality rate (52.8 percent).

Projections anticipate an increase in losses and damages from climate-induced disasters in the future, contributing to both economic and non-economic loss and damage (L&D). Responses to CC impacts necessitate plural institutions and managed approaches at local, regional, and national scales, addressing both rapid and slower-onset disasters. Changes in monsoon patterns in Nepal are expected to exacerbate poverty and inequality, necessitating effective strategies for economic and social progress in the face of long-term and short-term climate challenges.

Studies by Mehta and Shah [32] underscore the unfair impact of CC on agro-biodiversity, emphasizing the urgency of planning. Paudel and Andersen [33] critique the implementation process of the National Adaptation Programme of Action (NAPA), emphasizing the need for community-based adaptation plans. Khatri et al. [34] discuss the role of local-level community-based organizations (CBOs) and non-governmental organizations (NGOs) in supporting CC mitigation. Regmi and Bhandari [35] argue for effective CC policies addressing barriers in technology, knowledge, and institutional frameworks, advocating for changes in development design and planning. Pradhan [36] underscores the importance of recognizing traditional adaptation techniques. Mehata and Shah [37] note the gradual shift toward modern paddy varieties due to changing climatic factors. Molnar [38] discusses the impacts of seasonal rainfall pattern changes on crop production, animal systems, and human populations. Poudel [39] emphasizes the effects of weather fluctuations on agricultural production

in Kathmandu Valley, with shifts in the agriculture calendar. Similarly, Batenga et al. [40] highlight the decline in drinking water availability, affecting villagers' livelihoods. ISET-N [41] emphasizes the importance of a social scientist approach to studying adaptation capacities based on class, gender, and ethnicity.

The Ministry of Forest and Environment of Nepal identified Ramechhap district as the second most vulnerable in its NAPA Report submitted to the UNFCCC in 2010. Vaidya et al. [42] point out challenges faced by communities in the Southern belt of Ramechhap, including variable rainfall, drying water sources, crop failure, and loss of biodiversity. LAPA reports of Himalayan Resources Himalaya (2013) for Manthali, Khaniyapani, Himganga, and Chisapani [43–46] highlight changing temperatures impacting agricultural production and livelihoods. Upham et al. [47] stress the need to measure and understand environmental tenets and adaptive behaviors, cautioning against relying solely on environmental attitudes without corresponding behavior changes.

The discourse on CC in Nepal presents a multifaceted challenge requiring a comprehensive approach considering socioeconomic, environmental, and cultural factors for effective adaptation strategies. The investigation into the sociological impacts of CC on farmers in the Ramechhap district, Nepal, particularly those dependent on forests, agriculture, and livestock, aims to provide a nuanced understanding of daily challenges and vulnerabilities in this complex context.

4. Findings of the study

4.1 Climate change impact in the study area

4.1.1 Climate change impact to agriculture

Agricultural crops have been directly affected by drought in the Ramechhap district. According to the villagers, Maize crop has been directly affected by drought in the district. They argued that maize had been affected by drought. Therefore, it is very difficult to propagate maize properly.

It is miserable condition of the maize in 2014. Somlal Majhi (male, age 66) said, "Maize could not propagate properly due to the drought." Besides this, all maize was seen as drying, and very anxious moment was created in the life of the farmers. Similarly, Ratna Newar (male, age 53) said that villagers returned from brick kiln soon for cultivating maize but they were in the dilemma. The one had cultivated maize in two times but all are dried out. It is so distressing that he interrogated himself, "How could life exist?" A father of seven kids said that it was very difficult to sustain life in this year because who earned USD 758 to working in the brick kiln that will also finish soon because there is no any option of livelihood within 6 months. He hoped up to *Saas Chhaunjel Aas Vanejhai* (hope till last moment of respiration). He was trying to cultivate maize two times. He was hopeless of the maize cultivation for human. There was same situation for livestock. Farmers have got free time due to the drought so that all respondents of FGDs. They said satirically that *Sukhkha le Sukha Lyayo* (drought brought happiness). They made such a slogan expressing their pain.

Generally, July was supposed to be busy time for all farmers for cultivating and weeding of crops. They were seen free for utilizing their time for lice killing of head or talking to *Chautara (*a kind of traditional Platform*)*. Inhabitants can neither go for alternatives livelihood sources nor stay in the home so that they have to use free time in the gossiping and back biting others.

During staying in the *Chautara* inhabitants started backbiting of third person who did not appear at the informal meeting. Among backbiters, someone said that information of third person ultimately created conflict in family and community. One respondent said that whenever people were free from work, they spend time on backbiting and lead to fighting.

Therefore, it creates relationship problem between each other, and conflict has been created in society. Some farmers, whose farmland near Tamakoshi River, cultivate maize after irrigating from water pulling. But they are also not given satisfied maize production as like as rainfall. It is told by Som Rama Karki (woman, age 33) that the people used generators for pulling water from the Tamakoshi River from Manthali and Madhimuhan. The water had been pulled in the winter crops and maize sown, but it was not as good as a rainfall being happened from sky.

For winter maize, at least one to two times rainfall has been considered as good. There was uncertain rainfall in regular routine. Maize cultivation calendar in *Khet* (irrigated land) and *Bari* (unirrigated land) seem more fluctuated and fall behind rather than the past routine. Therefore, some farmers have used generator as an alternative source for irrigation. Concerning this issue, Satya Majhi (male, age 46) elaborated with the saying that farmers had waited rainfall for cultivating maize in last 5 years. He added that farmers have been using generator for water pulling otherwise no other option for irrigation (**Table 1**).

The presented table illustrates the discernible impacts of CC on agricultural production in the Ramechhap area. Notably, the decrease in production over the last decade across various crops and types of land highlights the vulnerability of the region to changing climatic conditions. Paddy, wheat, and maize, cultivated on irrigated land, have experienced significant declines in production, with reduction rates of 55.46 %, 31.25 %, and 29.76%, respectively. Maize, grown on rainfed and slope land, also shows notable decreases of 46.66% and 33.76%, emphasizing the broad-ranging influence of CC on diverse types of agricultural landscapes.

Crop	Type of land	Production of local variety in Kg/Ropani		
		Last 10 years	Now	Decrease rate
Paddy	Irrigated land	256	142	55.46%
Wheat	Irrigated land	128	40	31.25%
Maize	Irrigated land	168	50	29.76%
	Rainfed land	210	98	46.66%
	Slope land	154	52	33.76%
Finger Millet	Irrigated land	158	158	0
Horse Gram	Rainfed land	122	42	34.42%
	Slope land	124	38	30.64%
Rice Beans	Rainfed land	158	56	35.44%
	Slope land	162	62	38.27

Source: FGDs in 2023.
Note: Ropani is a land measuring unit in Nepal consisting of 508.722 square meters/Ropani.

Table 1.
Agricultural production status in Ramechhap.

Interestingly, finger millet on irrigated land remains unaffected, showing a consistent production level over the past decade. However, horse gram and rice beans, cultivated on rainfed and slope land, exhibit decrease rates of 34.42% to 38.27%, indicating the pervasive impact of CC on various crops and land types. These findings underscore the urgent need for adaptive strategies and resilient agricultural practices in the face of CC, aiming to safeguard food security and livelihoods in the Ramechhap, Nepal.

This text emphasizes the profound repercussions of CC, particularly drought, in the Ramechhap district of Nepal. The agricultural sector, primarily reliant on maize cultivation, confronted significant challenges as crops withered, leaving farmers distressed and despondent. Even the implementation of drought-resistant hybrid maize proved unsuccessful, exacerbating the agricultural crisis. The societal implications were evident in disrupted routines, with farmers returning from brick kilns to uncertain prospects, and livestock suffering due to the absence of rainfall. The adverse conditions resulted in increased free time for farmers, which, unfortunately, manifested in negative social consequences such as backbiting and conflicts within the community. The dependence on alternative water sources, such as pumping up from the Tamakoshi River, did not yield satisfactory results compared to natural rainfall. Social media posts mirrored the community's concerns, with cultural practices like frog marriage ceremonies emerging as desperate attempts to invoke rain. The overall decline in agricultural production over the past decade, as indicated by data and case studies, has not only impacted livelihoods but also disrupted the social fabric, compelling families to procure essential crops from the market and challenging their societal standing. This situation underscores the intricate interplay between climate-induced challenges and the nuanced social dynamics of the affected region. It is revealed that production of the cereal crops is decreasing due to the prolonged drought in the study area. However, there are some other factors like less farm yard manuring, untimely cultivation, poor seed quality, damaged by wildlife, pest attack, and diseases are also responsible for the less production to some extent.

In a more personal perspective, Manamaya Tamang, a resident deeply ingrained in the fabric of Ramechhap, provides a poignant viewpoint on the overwhelming impact of CC in the district. From Manamaya's standpoint, the reliance on maize cultivation, a cornerstone of the agricultural sector, has encountered formidable challenges with the onslaught of drought. The distress and hopelessness etched on the faces of farmers resonate with the gravity of the situation, as even the touted drought-resistant hybrid maize failed to salvage the agricultural crisis, plunging the community into deeper despair.

Manamaya sheds light on the societal aftermath, where disrupted routines force farmers to return from brick kilns to a landscape of uncertainty. Livestock, integral to the community's livelihood, suffers in the absence of rainfall, painting a grim picture of the challenges faced by the agricultural sector. The surplus free time, a consequence of adverse conditions, unfortunately, manifests in negative social repercussions, with instances of backbiting and conflicts surfacing within the community.

The reliance on alternative water sources, exemplified by the Tamakoshi River, does not provide the expected respite compared to the natural rainfall. Manamaya underscores the palpable concern within the community, evident in social media posts reflecting their collective anxiety. The desperation to seek rain, symbolized by cultural practices like frog marriage ceremonies, highlights the lengths to which the community goes to restore balance in the face of environmental upheaval.

As Harimaya another respondent reflects on the overall decline in agricultural production, the data and case studies presented over the past decade underscore the far-reaching

consequences. The necessity for families to purchase essential crops from the market adds an economic strain, challenging the societal prestige they once held. Through Harimaya's lens, the intricate interplay between climate-induced challenges and the delicate social dynamics of the affected region comes into sharp focus, urging a collective response to safeguard both livelihoods and the cultural tapestry that defines Ramechhap.

4.2 Climate change impact to livestock

The impact of CC on livestock farming in Ramechhap is evident in the diminishing numbers of livestock, particularly cows. Various factors contribute to this decline, influenced by evolving national, international, and global environments, alongside the direct effects of CC. This has resulted in a gradual reduction in livestock farming, a primary source of subsistence in Ramechhap. Economic, social, and cultural considerations are prompting farmers to decrease their livestock holdings.

Kale Majhi, an experienced farmer in Ramechhap, vividly illustrates the impact of CC on livestock farming, expressing deep concern over the decreasing numbers of livestock, especially cows. He attributes this decline to a confluence of factors, including the changing national, international, and global environments intricately linked with the repercussions of CC. Kale emphasizes the interplay of economic, social, and cultural considerations, underscoring how these factors compel farmers to make the challenging decision of reducing their livestock holdings in response to the evolving challenges posed by CC.

The enrolment of children into schools has contributed to a decrease in child labor for livestock rearing and care, further diminishing the number of livestock per household. Traditional practices like transhumance, where livestock was brought to Marinakhola Sindhuli for 6 months, were discontinued after 2010, impacting the management of a significant number of livestock in Ramechhap.

Ram Dhungel, a long-time observer of local dynamics in Ramechhap, provides insightful narratives on the multifaceted factors influencing the decline in livestock numbers. He notes that the entry of children into schools has been transformative, improving education but also reducing available child labor for traditional livestock rearing and care, thereby playing a significant role in the overall decrease in livestock per household. Ram also emphasizes the impact of historical changes on traditional practices, such as transhumance, contributing to the observed decline.

The initiation of the community forestry program in 1992 altered the landscape, resulting in the control of open grazing lands and impacting livestock rearing practices, further contributing to the decline in livestock numbers. Prolonged drought periods have led to a scarcity of fodder and grass in both self-owned and publicly owned lands, exacerbating the gradual decrease in livestock numbers.

The migration of the younger generation to countries like Malaysia, South Korea, and Middle East for labor work, driven by joblessness in Nepal, has resulted in a lack of young people in the area to care for livestock, further contributing to the decline. Additionally, farmers are increasingly shifting to tractors instead of traditional yoke and oxen for plowing due to their efficiency, time-saving nature, and the ability to work in difficult terrain. The preference for tractors is partly driven by increasing drought in the area, resulting in a scarcity of fodder for oxen.

Economically, tractors are considered more cost-effective and efficient compared to oxen, prompting farmers to prefer tractor services. This transition from traditional livestock farming practices to modern technologies reflects broader societal changes influenced by economic, environmental, and technological factors, raising concerns

about the potential displacement of traditional practices and the need for adaptation strategies in the face of CC.

Samita Majhi, an astute observer of the changing agricultural landscape in Ramechhap, provides valuable insights into the factors contributing to the decline in livestock numbers. According to Samita, the migration of the younger generation to countries like Malaysia and Qatar for labor work has created a significant void in the community, impacting the care for livestock traditionally handled by young individuals. Furthermore, Samita highlights the shifting preferences of local farmers toward tractors over traditional yoke and oxen for plowing, driven by considerations of efficiency, time-saving benefits, and the ability to navigate difficult terrain. This transition is, in part, a response to the increasing frequency of drought in the region, resulting in a scarcity of fodder for oxen.

Economically, Samita underscores that tractors are perceived as more cost-effective and efficient, leading farmers to willingly invest in tractor services. The adoption of tractors is viewed as a practical and modern approach to agriculture, aligning with the changing economic, environmental, and technological landscape of the area. Samita's perspective on this transition underscores broader societal changes influenced by various factors, including climate-induced challenges, and raises important considerations about the potential displacement of traditional practices and the necessity for adaptation strategies in the face of CC.

4.3 Climate change impacts to forest and wildlife

The prolonged drought has taken a toll on the forest, causing it to dry out. Pine (*Salla*) tree leaves, crucial for forest health, require sufficient rainfall to decompose, a condition that has been lacking due to the extended dry period. The forests have experienced degradation, attributed to both human interference and the scarcity of rainfall. Many forest species, including drought-resistant ones, have withered. Pine species, from saplings to mature trees, and various coniferous and broad-leaved species have all been affected by the severe drought, leading to their drying out. The decrease in the number of seedlings growing in the forest is apparent, as pine seeds struggle to germinate and non-flowering trees wither due to the persistent drought.

Impact of CC on the forest is evident in multiple facets. Firstly, the forest has become arid, and secondly, invasive species have proliferated unevenly, leading to irregular flowering and an increase in deforestation due to recurrent droughts. Naina Kumari Majhi, a 76-year-old woman, emphasized the critical issue of pine seed regeneration, expressing concerns that repeated droughts might hinder the future regeneration of pine seeds. Additionally, other broad-leaved species like *Chilaune, Phosro, Khayer, Gidari, Kutmiro,* and *Dhangero* have also suffered from drying out in recent years.

Commercial trees have not been spared, impacting industries like Tamakoshi Forest Product Limited (TFPL), which ceased *Bel* (a drought tolerant species in the district) juice production due to insufficient Bel fruit production caused by less rainfall and smaller fruit growth. The drying out of *Bel* trees since 2010, coupled with yearly droughts, has significantly reduced its fruit production. Himal Dhungel, a local journalist, pointed out the unintended consequences of the Government of Nepal's experiment with planting pine species for greenery, resulting in the drying out of local water resources.

Furthermore, the decrease in Simal trees in the locality has been attributed to CC, long-term drought, and a lack of attention to conservation. Dan Bahadur Karki highlighted the decline in the utility of *Simal* trees, once used for boat construction.

He mentioned that *Simal* wood is not ideal due to its smokiness and lack of durability. The flowering time of *Simal*, a crucial factor for its ecosystem, has been affected by climatic changes.

Infrastructure development, road construction, and vehicle emissions, particularly CO_2, have been linked to environmental changes. Local communities believe that CO_2 emissions contribute to pushing away clouds, thereby affecting rainfall patterns. The increase in population and inadequate regulations against illegal logging have further accelerated forest degradation. Barren land and decreased land productivity have led to food insecurity, significantly impacting the lives of people.

From an environmental perspective, pollution from vehicle emissions has added to the challenges faced by local communities, affecting respiratory health and contributing to problematic situations in surrounding areas. The interconnectedness of CC, human activities, and environmental impacts underscores the multifaceted challenges faced by both the forest and the community.

The prolonged drought has taken a toll on the forest, causing it to dry out. Pine tree leaves, crucial for forest health, require sufficient rainfall to decompose, a condition that has been lacking due to the extended dry period. The forests have experienced degradation, attributed to both human interference and the scarcity of rainfall. Many forest species, including drought-resistant ones, have withered. Pine species, from saplings to mature trees, and various coniferous and broad-leaved species have all been affected by the severe drought, leading to their drying out. The decrease in the number of seedlings growing in the forest is apparent, as pine seeds struggle to germinate and non-flowering trees wither due to the persistent drought.

4.4 Drought impact to local forest health

Persistent drought has resulted in the desiccation of forests, hindering the decomposition of pine tree leaves—a process traditionally dependent on ample rainfall. This has led to adverse effects, with both young and mature pine trees fading due to consecutive droughts, and coniferous and broad-leaved species experiencing a decline in overall forest health. Scientific literature extensively addresses the ecological impacts of prolonged dry periods, emphasizing how climatic stressors impede crucial decomposition processes [48].

Human activities have further aggravated forest degradation, heightening the vulnerability of various species, including those adapted to withstand drought conditions. Walker et al. [49] highlights the cascading effects of drought on forest composition, indicating that anthropogenic factors contribute to the withering of drought-resistant species. Deforestation, resource overexploitation, and other human-induced stressors collectively compromise forest resilience, rendering them more susceptible to climate-driven impacts.

Naina Kumari Majhi's witnessed observation regarding the failure of pine seeds to germinate underscores a critical concern for future forest health. Her insights highlight compromised regeneration potential, posing significant long-term sustainability implications for the forest ecosystem. Additionally, the drying trend extends beyond coniferous species to various broadleaved species, aligning with recent studies emphasizing the vulnerability of diverse tree species to CC conditions [50].

The observed fading of pine trees and the broader decline in coniferous and broad-leaved species signify the severity of consecutive droughts. Peterson et al. [51] explain how extended water scarcity induces physiological stress in tree species, resulting in diminished forest health. This underscores the urgency for comprehensive

conservation measures and sustainable management practices in the face of climate-induced challenges.

The decline in forest regeneration, particularly the reduction in seedling abundance, is a critical concern with far-reaching consequences. Historical records highlight the forest's erstwhile richness in seedlings, serving as an essential component of biodiversity. Recent trends reveal a disconcerting decrease, attributed to challenges faced by pine seeds in germination and the withering of non-flowering trees due to prolonged drought conditions.

Empirical evidence supports the assertion that CC has ushered in a dual impact on the forest ecosystem. The drying out of the forest, documented in studies such as Smith et al. [52], underscores adverse effects from reduced precipitation and increased evaporation, contributing to vegetation desiccation and ecological imbalances. Afforestation initiatives, while well-intentioned, add complexity to ecological challenges, inadvertently contributing to the drying of local water resources [53].

4.5 Change of flowering season of forest species

The flowering seasons of forest species have undergone a notable shift, occurring 1 to 2 months earlier than their historical patterns. This change strongly suggests an increase in temperatures over time. The explicit illustration of this phenomenon is presented in the following table, showcasing the altered flowering times of various species compared to their general routine. The observed shifts in flowering seasons serve as tangible indicators of the warming climate and its impact on the phenology of forest ecosystems. In addition to the fruits highlighted in **Table 2**, there have been noticeable shifts in the flowering, leaf-shedding, and fruiting times of various other tree species. For instance, the traditional flowering period of *Koiralo*, which previously spanned from February to April, has advanced to the 3rd week of January. *Chilaune*, known for flowering in April–May, now blooms in March–April. The leaf-shedding patterns have also experienced a shift, occurring earlier in February–March, compared to the previous timeframe of April–May.

Name	Before 1990 A.D.		2023 A.D.	
	Flowering time	Ripening time	Flowering time	Ripening time
Mango	1st week of February	June, July August	Middle of December and January	April, May, June, July
Pineapple	1st week of February	June–July, August–September	December	May, June, July, August
Custard Apple	Middle of April	July–August, September–October	May, June, July	August, September
Pomegranate	1st week of February	September–October, November–December	December	July, August, September
Lemon, Citrus fruits	In between January and February	November–December, January–February	December	August, September, October

Source: Focused Group Discussion in 2023.

Table 2.
Flowering time and ripening time of various tree species.

Furthermore, the flowering season of *Simal*, once limited to March–May, now initiates in January–February. *Simal* and *Kaiyo* have unexpectedly commenced flowering in this season ahead of their usual schedule. CC has played a discernible role in altering the flowering seasons of these plants. Leaf shedding, traditionally occurring in April–May, now starts as early as February and March. The *Simal* tree, originally flowering in March/April/May, has shifted its flowering season to commence in January. These changes underscore the impact of CC on the phenology of various tree species, influencing not only flowering times but also the shedding of leaves.

4.6 Invasive species are major problems of forest ecosystem

Proliferation of invasive species, irregular flowering patterns, and heightened deforestation are consequential outcomes of recurring drought events. Leishman et al. [54] conducted studies delving into the intricate relationship between climate change, modified precipitation patterns, and the subsequent proliferation of invasive species. Flourishing in arid conditions induced by drought, these invasive plants disrupt the natural balance of ecosystems, contributing to observed uneven flowering and increased deforestation.

The invasion of new plant species, such as *Seto Banmara*, has adversely affected crops and forest cover, with Ram Tamang (76) noting the aggressive spread of these invasive species over the past decade. While *Seto Banmara* aids in water filtration, it has displaced the abundant *Sitho* grass species, rendering the forest more susceptible to fires. Nara Shrestha (48) highlighted the transformation of once lush forests into barren land due to reduced rainfall, impacting even drought-resistant species like *Bel* and *Khayar*.

The emergence of alien invasive species, including *Twakejhar* grass, has been observed in the study area, covering agricultural land after unseasonal rainfall. This grass, harmful to both humans and cattle, exacerbates the challenges faced by the community. The decline in dried forest products, once a source of income for the poor, has led to barren forests that were once abundant with grass for animal pasture.

The invasion of new plant species, as exemplified by *Seto Banmara*, has significantly impacted both crops and forest ecosystems. Fatman Tamang's observation of the aggressive spread of these invasive species over the past decade is substantiated by recent studies on invasive plant species dynamics [55]. However, *Seto Banmara* contributes increase in water filtration, as noted by Tamang, aligns with findings on the ecological functions of invasive species in altering ecosystem processes [56].

4.7 Closure of Tamakoshi forest products limited

The detrimental effects of CC extend beyond ecological realms, significantly impacting local forest-based enterprises and communities reliant on forest resources. Commercial trees, essential for sustaining enterprises like TFPL, fall victim to changing climate patterns, particularly recurrent droughts in the region.

Bahadur Khadka (66 years old) sheds light on the economic repercussions, emphasizing the decline in *Bel* fruit production due to low rainfall. This has compelled TFPL to halt *Bel* juice production, affecting the local economy and employment. These findings align with studies by Sharma et al. [57], underlining the vulnerability of commercial crops to shifting precipitation patterns and extreme weather events.

Observations of diminishing rainfall and smaller *Bel* fruits since 2010 underscore the persistent climate-induced challenges faced by the region. Studies, including

those by the IPCC [6], discuss the intensification of drought conditions as a consequence of global CC, validating experiences shared by Bahadur Khadka.

A local school principal proposed alternatives for forest rehabilitation, suggesting planting trees like *Chilaune* and *Dhangero*. With no significant rainfall in the last 4 years, there are concerns that *Bel* could be lost within 5 years. The principal recommended planting *Ashok* and *Rudraksha* for environmental protection. Dan Karki highlighted the gradual decline of *Simal* trees due to climatic changes and prolonged drought, further aggravated by neglect in conservation efforts.

The local school principal's proposal for forest rehabilitation, endorsing the planting of trees such as *Chilaune* and *Dhangero*, aligns with ecological experts' recommendations. Studies by Sharma et al. [58] support afforestation with indigenous species, proving effective in restoring degraded ecosystems and enhancing biodiversity.

The alarming decrease in *Bel* population over the last 4 years, attributed to prolonged drought, aligns with findings by Jackson et al. [59]. Their research emphasizes the vulnerability of specific tree species, like *Bel*, to changing climatic conditions, emphasizing the urgency of targeted conservation and rehabilitation initiatives.

Dan Karki's observations regarding the gradual decline of *Simal* trees due to CC and prolonged drought align with broader research on the vulnerability of various tree species to shifting climate patterns [60]. Additionally, Lackner et al. [61] highlight the importance of conservation efforts in preventing further losses in tree diversity and ecosystem health.

These recommendations underscore the need for a comprehensive and context-specific approach to forest rehabilitation, combining local knowledge with scientific insights to address the unique challenges posed by CC and human activities.

The impact of persistent drought on the forest ecosystem and local communities is a matter of critical concern, warranting comprehensive analysis and proposed interventions. The ongoing desiccation of forests, exemplified by the decomposition challenges of *pine* tree leaves, underscores the urgent need for adaptive strategies. As highlighted by Pile et al. [62], prolonged dry spells pose a significant threat to forest health, disrupting ecological processes and leading to the decline of various tree species.

Human activities exacerbate the degradation of forests, further intensifying the challenges posed by CC. The findings of the IPCC [63] emphasize the interconnectedness of human-induced factors and environmental degradation, illustrating the need for sustainable practices and conservation efforts.

Moreover, the invasion of new species, uneven flowering, and increased deforestation are identified consequences of CC in the region. These challenges resonate with the research by Demertzis and Iliadis [64], who discuss the cascading effects of CC on forest ecosystems, including altered species composition and increased vulnerability to invasive species.

Addressing these multifaceted issues requires a holistic approach. Proposed interventions should consider community engagement, sustainable forest management practices, and region-specific climate adaptation strategies. The work of Mwangi et al. [65] highlights the importance of community involvement and adaptive governance structures in fostering resilience to climate-induced ecological changes.

The proposed interventions should draw upon a robust understanding of the ecological intricacies and the interconnectedness of CC impacts on forests and local communities. Traditional practices like crossing rivers on boats made from the light wood of *Simal* have been affected. It, while not ideal for wood and firewood, played a crucial role in local river crossings. Infrastructure development, including road construction and vehicle emissions contributing to CO_2 levels, is believed by

the community to influence rainfall patterns. The population increase and lax rules on illegal logging have intensified forest degradation, resulting in barren land and reduced land productivity, leading to food insecurity.

Nara Bahadur Shrestha's depiction of once lush forests turning into bare land due to reduced rainfall finds support in studies documenting the effects of CC on forest ecosystems [66]. The vulnerability of drought-resistant species like *Bel* and *Khayar* to changing climatic conditions underscores the broader implications of CC on forest biodiversity and ecosystem stability [67, 68].

The appearance of alien invasive species like *Twakejhar* grass after unseasonal rainfall, as mentioned by Shrestha [69], corresponds with documented instances of invasive species proliferation following extreme weather events [70]. The harmful effects of *Twakejhar* grass on both humans and cattle highlight the urgent need for effective management strategies to mitigate the impacts of invasive species on local communities [71].

The decline in dried forest products, once a vital source of income for the poor, mirrors broader trends in forest degradation and loss of ecosystem services [72]. The shift in forest management from Government to CFUGs, as described by Shrestha [69], reflects broader shifts in governance structures and their implications for local livelihoods [73].

The observed changes in flowering seasons, ripening times, and the transformation of leaves into thorny species are consistent with documented impacts of CC on phenological patterns and plant adaptations [74]. Mr. Kul Karki's observation of leaves transforming into thorns as a survival adaptation to prolonged drought highlights the complex interplay between CC and vegetation dynamics [75].

The shift in flowering seasons, ripening times, and even the transformation of leaves into thorny species are attributed to CC impacts. The altered timings of *mango, pineapple, custard apple*, *pomegranate*, and *citrus* fruits indicate a shift in climate patterns. Mr. Kul Bahadur Karki observed the transformation of leaves into thorns in response to the prolonged drought, a survival adaptation in vegetation.

The social organization has suffered as CFUGs' members are reluctant to attend meetings, attributing the lack of interest to the perceived futility of discussing barren forests. The rich are more inclined toward forest protection, while the poor prioritize fulfilling their livelihood needs, potentially leading to conflicts between these groups. This social disruption has contributed to increased timber demand, resulting in haphazard tree cutting, deforestation, and diminished forest and plant vitality due to recurrent droughts.

The theory aligning the rise in atmospheric temperature with drought onset and food grain scarcity contributing to class conflict, criminal activity in deforestation, and structural, functional, conflict interactional, economic sociological, and criminological aspects is evident. The negative changes in social living patterns are a consequence of the disastrous impacts from the intersection of CC and social–ecological patterns in geography.

4.8 Wildlife trouble to village people

Local residents report a noticeable surge in wildlife intrusion into their village, attributing this phenomenon to the effects of CC. Consequently, agricultural crops cultivated by the local population have suffered extensive damage, with animals such as monkeys, porcupines, and deer identified as the culprits. This escalating wildlife presence has led to the destruction of vital crops, negatively impacting the livelihoods

of the villagers. The lack of wild foods and fruits in the region exacerbates the situation, intensifying the strain on the community's sustenance.

Numerous studies support the assertion that CC can drive shifts in wildlife behavior and distribution. For instance, the IPCC, in its report on climate impacts, highlights the potential disruptions to ecosystems and species distribution due to changing climate patterns [76]. Additionally, research by the World Wildlife Fund (WWF) underscores the connection between CC and alterations in wildlife behavior, with potential consequences for human communities [77].

This compelling evidence substantiates the claim that CC-induced alterations in wildlife patterns are adversely affecting the agricultural landscape in the village, thereby jeopardizing the local residents' livelihoods.

Researchers' observations indicate a pronounced escalation in drought conditions in the southern part of Ramechhap. This intensifying aridity poses significant challenges for effective forest management in the region. Plantation efforts are particularly hindered as the scarcity of water makes it impractical to irrigate and sustain newly planted vegetation, leading to the widespread destruction of these efforts.

This observation aligns with broader concerns about changing precipitation patterns and increased drought frequency associated with CC. Studies such as the National Climate Assessment in the United States highlight the growing risk of droughts in various regions due to climate-related factors [78]. Additionally, the IPCC reports on the global impacts of CC, emphasizing the vulnerability of ecosystems, including forests, to altered water availability [67, 68].

The empirical evidence from these reputable sources reinforces the researchers' on-the-ground observations, emphasizing the pressing issue of escalating drought conditions in the southern part of Ramechhap and its adverse effects on forest management and plantation initiatives.

Poudel, a local resident in the southern part of Ramechhap, echoes the sentiments of the community concerning the noticeable increase in wildlife intrusion attributed to CC effects. As a witness to the consequential damage to agricultural crops caused by animals like monkeys, porcupines, and bears, Poudel emphasizes the dire impact on the villagers' livelihoods. The absence of wild foods and fruits further compounds the challenges faced by the community, accentuating the strain on sustenance.

Moreover, Poudel shares the concern about escalating drought conditions in the region, particularly in the southern part of Ramechhap. The intensifying aridity poses formidable challenges for effective forest management, hindering plantation efforts due to water scarcity. As someone directly affected by these conditions, Poudel emphasizes the practical difficulties in irrigating and sustaining newly planted vegetation, leading to widespread destruction.

Susil Poudel's perspective aligns with broader scientific assessments, drawing attention to changing precipitation patterns and increased drought frequency associated with CC. The National Climate Assessment in the United States and reports from the IPCC serve as crucial references supporting the local observations. Poudel's voice adds a personal dimension to the empirical evidence, highlighting the urgency of addressing the pressing issue of escalating drought conditions and their detrimental effects on both wildlife and forest management initiatives in the southern part of Ramechhap.

4.9 Disturbance to community forestry user group (CFUG)

Members of the CFUGs have exhibited reluctance to attend meetings, and locals have been unwilling to participate in discussions, citing a perceived lack of necessity

for dialog concerning the barren and dried state of the forest. Quorum requirements for meetings have frequently gone unfulfilled, as exemplified by a meeting called by a local leader a year ago that saw minimal attendance. Expressing concerns about the desiccated condition of the forest, Kumar Majhi (57 years old) highlighted the rise in forest product theft, contributing to a diminished interest among the community. It is also revealed that forest fire in the forest area including community forest area has been increased in recent years due to the invasive species growth and high deposit of inflammable materials such as dry leaflitter, dried twigs and tops, and increased temperature in the area. Moreover, 13 arm forces were killed in 2013 in Ramechhap while they were involved in forest fire extinguishing in a community forest area. Additionally, the planted species were died in the forest due to increased drought and temperature in Ramechhap.

Notably, there appears to be a divide in perspectives, with affluent individuals showing greater interest in forest protection, while economically disadvantaged individuals prioritize meeting their livelihood needs. This dichotomy could potentially escalate into conflicts between the affluent and impoverished classes. Consequently, the increased demand for timber has led to rampant and unsustainable tree cutting, exacerbating the issue of deforestation. The adverse impacts on the forest and vegetation are further compounded by recurring and prolonged droughts in recent years.

As a consequence of severe drought impacts, the CFUG committee has faced challenges in fulfilling its responsibilities in forest management. Hari Poudel, serving as the Chairperson of Ramite CFUG, contends that the once-significant role of community forest (CF) has diminished. This decline is primarily attributed to a pervasive lack of concern among the general populace for these arid woodland areas. Similarly, Min Shrestha from the CFUG of Sallaghari observes a growing trend of young people migrating abroad in search of better opportunities. This migration has resulted in decreased interest among the youth to actively participate in the CFUG committee.

Hari Poudel expresses concern over the severe impacts of drought on the CFUG committee, emphasizing their inability to fulfill their responsibilities in forest management. As the Chairperson of Ramite CFUG, Poudel argues that the once-significant role of CF has diminished, largely attributed to a pervasive lack of concern among the general populace for these arid woodland areas. In a similar vein, Min Shrestha, representing the CFUG of Sallaghari, highlights a troubling trend of young people migrating abroad in pursuit of better opportunities. This migration phenomenon has led to a decline in the youth's interest and active participation in the CFUG committee. Shrestha expresses deep concerns regarding the future sustainability of the CFUG, foreseeing a potential crisis post the older generation's passing. The reluctance of the younger population to engage is fueled by their frustration with the profound impacts of CC, posing a significant threat to the continuity of CF management efforts.

In analyzing this scenario, theoretical frameworks such as structural–functional, conflict interactional, economic sociological, and criminological perspectives can be applied. The rise in atmospheric temperature, coupled with prolonged droughts and food scarcity, can be viewed as contributing factors to class conflict, criminal activities linked to deforestation for financial gain, and negative changes in social living patterns. These dynamics reflect the interconnectedness of social and ecological patterns within the geographic context, showcasing the multifaceted impacts on the community.

5. Conclusion

In conclusion, this study has ventured beyond conventional biophysical perspectives to illuminate the sociological dimensions of CC, particularly in the context of the Ramechhap district in Nepal. Employing a sociological lens and drawing inspiration from constructivist theory and the complex human–environment systems (CHANS) framework, our research navigated through institutional, structural, and societal pathways of adaptation.

The qualitative nature of the study, characterized by purposive sampling and ethnographic methods—snowball-sampling technique, allowed for a nuanced exploration of local perceptions and experiences. Diverse respondents representing communities reliant on forests, agriculture, and livestock contributed to a holistic understanding of the intricate dynamics shaping their responses to CC.

Global warming emerged as a formidable force, imposing daily challenges on farmers in Ramechhap. The increased prevalence of drought, temperature fluctuations, and altered monsoons disrupted the agricultural system, leaving it vulnerable and less productive. In the face of these challenges, farmers exhibited resilience and resourcefulness by implementing adaptive measures rooted in traditional and local knowledge, coupled with the integration of new technologies and skills.

The study highlighted nuanced strategies employed by the community, such as adjusting crop varieties based on climate disturbances and fostering collective networks through the exchange of experiences. These sociological insights offer valuable contributions to the formulation of more comprehensive CC policies, recognizing the importance of local knowledge and adaptive capacities.

As the research unfolded, it not only presented a detailed understanding of the challenges faced by communities in Ramechhap but also underscored the adaptive capacities and resourcefulness demonstrated by farmers in response to the evolving climate. The methodological approach employed in this study, guided by a sociological lens, serves as a potential model for similar investigations in regions grappling with comparable challenges, aiming to broaden our understanding of the human dimensions of CC.

In essence, the objective of this study was met by providing a comprehensive exploration of the sociological impacts of CC on forest user groups and forest management in the Ramechhap district. The findings emphasize the interconnectedness of environmental and societal factors, urging a holistic and community-centric approach to CC mitigation and adaptation efforts.

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Section 4

Agroforestry

Chapter 9

Agroforestry Responses to 20 Years of Agricultural Expansion in the Central Highlands of Vietnam

Da B. Tran and Duc Vien Tran

Abstract

Vietnam's Central Highlands, under the 'boom' of increased immigrant populations, forest loss, and agriculture expansion, have been facing unbalanced and unsustainable development. This study determines the existence of agroforestry in the region and how farmers responded to the expansion of agriculture over decades by secondary and survey data from 248 households of 20 communes in five provinces. After decades of mono-agriculture development, farmers faced a range of problems and consequently began applying agroforestry practices. About 65% of the surveyed households applied agroforestry and multi/inter-crop systems, but almost all the households were small farms. Agroforestry at both the farm and landscape levels existed and featured diversity. Plant and animal diversity in the agroforestry systems of the households was rich. We recommend that upgrading the agroforestry level can likely cope with the requirements of market-based production and also provide basic benefits. Thus, to help conserve the forests, improve the farmers' livelihoods, and protect the ecosystem in the Central Highlands and the whole of Vietnam, a National Agroforestry Policy and technical guides for agroforestry at both the farm and landscape levels should be launched together to approach the market-based productions of cash crops and agricultural circular economic development in Vietnam and tropical regions.

Keywords: cultivation, crop, forest, highland, households (HHs), sustainability

1. Introduction

Vietnam's Central Highlands, known as a wealthy and unique area, have become a sensitive and unstable region over the past 20 years. Even though it has always been considered as one of the most strategically important economic and political regions by the government, and has become a major agricultural commodity production region of the nation by producing key national products high in market demand and bringing in multi-billion-USD export revenue each year, a lot of issues have developed during this time. First, natural resources, including minerals, soil, water, and forests, have been exploited to the point of exhaustion. Natural forest destruction and devastation, both legally and illegally, have been very serious problems during this long period. For example, in 2015, competent agencies uncovered 6034 cases of violations of regulations on forest protection and development, up 463 cases from the figure

recorded in 2014 (equivalent to 8.3% of cases) [1]. The government closed the forests in 2016, but forest devastation still happens even inside the state-owned organizations [2]. Second, the rapid increase of land conversion for agriculture, especially the rise of cash crops, has become one of the major reasons for forest loss. Agricultural economic development in the region has resulted in trade-offs among economic, environmental, and social objectives in the process of sustainable rural development. For instance, robusta coffee in the Central Highlands of Vietnam has become one of the most intensive and concentrated areas of coffee production in the world; however, it is cultivated by smallholders as an un-shaded and clean-weeded mono crop [3]. Mono cultivation always faces a lot of risks such as natural disasters, diseases, market fluctuations, and a high dependence on outside inputs for the production systems. Although agricultural production brings billions of dollars to Vietnam, the Central Highlands are still one of the poorest regions. In 2018, the average rate of poor households in the Central Highlands was 11.4% (excepting Lam Dong Province – only 2.85%), while the average rate of poor households in all of Vietnam was 5.3% [4]. In addition, the region has faced increasingly more frequent serious droughts, which are the result of climate change and which strongly impact both agriculture and the livelihood of farmers, especially ethnic minorities. Climate change, however, has been poorly understood by farmers and other rural stakeholders [3]. The population has boomed, particularly uncontrolled immigration which was the strongest during the decades when high coffee prices stimulated migration from Central and North Vietnam to the Central Highlands [5], and it is continuous growth that has become a social issue. Last, many types of conflicts have happened and continue to happen. Since 1990, many environmental problems have occurred that can be grouped into 16 types of conflicts that are particularly linked to natural resource use and management [6].

Therefore, under the 'boom' of immigration, forest loss, and agriculture expansion, the Central Highlands of Vietnam face unbalanced and unsustainable development. The explosion of mono-cultivated cash crops focusing on rubber, coffee, and black pepper that farmers have grown freely without the control of the government has not served to improve the development of the region wholly. After decades of growing these cash crops driven by market demands, most of the farmers have failed because they caught the tail of the market signals. Due to the fact that state planning and the markets for cash crops were broken, farmers in the Central Highlands were also bankrupt [7]. So, how can farmers be aware of and how can they respond to these problems?

Agroforestry is a possible solution and an adaptable choice for small farmers in the Central Highlands, which will be discussed further in the research results. Thus, this paper seeks to determine the current status of agroforestry as applied by households to understand whether agroforestry has responded to the expansion of agriculture in the Central Highlands over the past few decades and then discusses further recommendations for sustainable development at both the local and regional scales.

2. Study sites and methods

2.1 Study location

Vietnam's Central Highlands include five provinces, namely Gia Lai, Kon Tum, Dak Lak, Dak Nong, and Lam Dong. **Figure 1** shows the study sites distributed over the ecosystem zones of the region (e.g., Ngoc Linh Mountains; Sa Thay lower mountains; Play Ku and Con Ha Nung Highlands; An Khe lower mountains; Cheo Reo, Phu

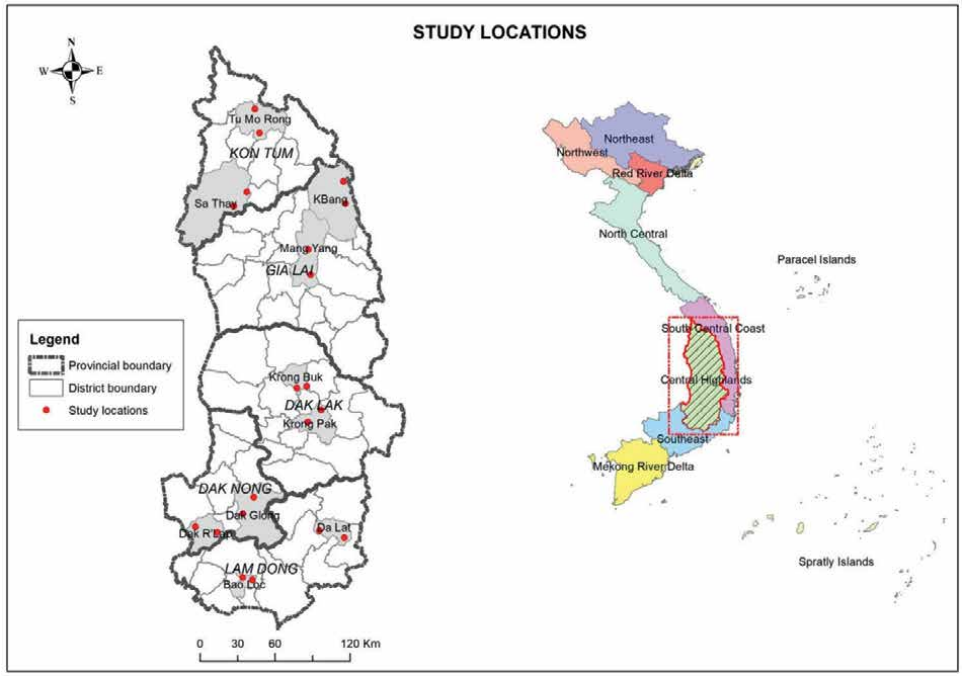


Figure 1.
Study sites in the central highlands, Vietnam (Source: Map based on information from the Department of Survey, mapping, and geographic information Vietnam).

Bon, and Ea Sup Semi-plateau; Buon Me Thuat Highland; Man Drak mountains; Dak Nong, Dak Min Highlands; Chu Ang Sin mountains – Da Lat Armenian Highland; and Di Linh, Bao Loc Highlands [8]).

2.2 Data and research methods

The series of major secondary data from 1999 to 2018 were collected from official legal documents. Of which, the data of the forest areas and coverages were from the Ministry of Agriculture and Rural Development (MARD), the data on the land areas were from the Ministry of Natural Resources and Environment (MNRE), and the others were from the Statistical Yearbooks of Vietnam. In addition, landsat images from Google Earth also were used in this research.

Primary data were collected from direct surveys given to 248 households in 89 villages of 20 communes belonging to ten districts of five provinces. The surveys were conducted at the end of 2018 and early 2019. Surveyed households were selected by the snowball sampling method. This approach involves two stages: (a) the identification of a sample of respondents with characteristic x at the zero-stage (s_0); and (b) the solicitation of referrals to other potentially eligible respondents believed to have characteristic x at snowball stages s_1 through s_k [9–11]. Applying this approach, the research conducted the zero-stage (s_0) at each of the 20 communes in the study locations; therefore, the number of villages and households surveyed was not equivalent.

Data were recorded, classified, and analyzed in Microsoft Excel (version 2010) and the R statistical software (version 3.5 in 2019) with the functions described by

ggplots and Kruskal–Wallis test [12]. Of which, the cultivation systems were divided into five types, namely: AF1 – agroforestry types including fruit, industrial, and wood trees; AF2 – agroforestry types including fruit and wood trees/industrial and wood trees; AF-others – other agroforestry types (different from AF1 and AF2); Agr – mono cultivation (only fruit tree or only industrial tree); and Agr-multi – multi-cultivation (mixed or intercroped fruits or/and industrial trees). The ethnic groups were divided into three major groups, namely: I – indigenous minority groups; K – Kinh group; and Others – other minority groups (immigrant minorities).

3. Results and discussion

3.1 A glance of 20 years of land use changes for agriculture expansion in the central highlands

Under the impacts of the economic development policies of the Vietnamese Government, agriculture activities in the Central Highlands were rapidly extended during the period from 1999 to 2018. Agriculture extensions are connected closely with forest degradation. The data in **Figure 2** present the changes of agricultural land areas, forest areas, and cover, and of the population over the time period. It can be seen that the increases in agriculture land (particularly perennial crop areas) and population are consistently together with the decreases in forest areas and cover, especially the decrease of natural forests. Specifically, in 1999, the total forest land was 2.99 million ha (including 2.93 million ha of natural forests) with a forest coverage of 56.8%, while agricultural land was 1.23 million ha (including 0.65 million ha of perennial crop areas); and in 2018, the total forest land was 2.56 million ha

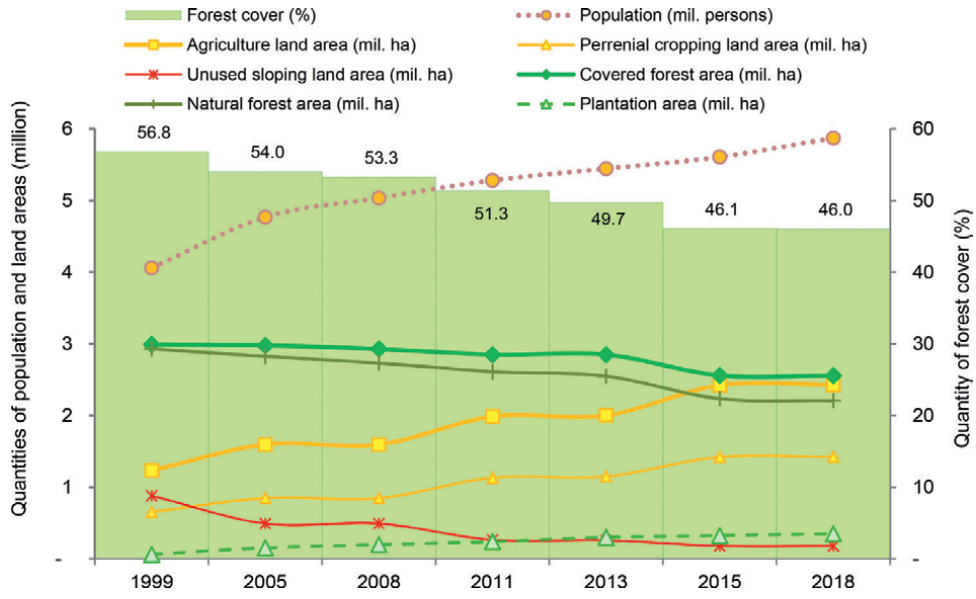


Figure 2.
Land areas, forest coverage, and population changes in the central highlands from 1999 to 2018. (Sources: Data from the Ministry of Agriculture and Rural Development (MARD), Ministry of Natural Resources and Environment (MNRE), and statistical yearbooks of Vietnam).

(a reduction of 14.0% compared to 1999), and the natural forest area was 2.21 million ha (a reduction of 24.7% compared to 1999) with the forest coverage of 46.0%, while agricultural land was 2.43 million ha (an increase of 96.8% compared to 1999) (of which, perennial crop areas were 1.42 million ha (an increase of 118.1% compared to 1999)). Additionally, hilly bare land was also considered to be linked to forest loss and reduced over the period from 0.88 million ha in 1999 to 0.18 million ha in 2018 (a reduction of 79.7%). Plantations slightly increased from 0.06 million ha in 1999 to 0.35 million ha in 2018 (an increase of 19.0%) but were not enough to replace the loss of natural forest areas in the region.

Before 2005, the major driver of land areas, forest coverage, and population changes in the Central Highlands was the economic development policies which targeted the building of new economic zones (NEZs) [5] with many state-owned agriculture enterprises (SAEs) and state-owned forest enterprises (SFEs). Until 2004, there was a total of 144 SAEs and SFEs that managed and used 2,012,721 ha of land area (of which, 59 SAEs managed and used 95,867 ha; and 85 SFEs managed and used 1,916,854 ha, including 1,046,047 ha of natural forests, 62,780 ha of plantation, and 214,938 ha of hilly bare land) [13]. Of note, before 2005, Dak Lak Province had 106 SAEs and SFEs that managed and used 1.65 million ha of land (occupying 86.13% of the total land of the province) with 20% of the total population (an average of 12.18 ha/person), while 80% of the population lived on the remaining land (an average of 0.53 ha/person) [14]. In regards to forestry, Dak Lak Province had 36 SFEs and 30 state-owned companies, which mainly harvested and sawed timber. They annually exploited about 400,000 m^3 of round timber and planted 10,500 ha of plantation [15]. At that time, agricultural cultivation was plan-based, consisting of mono-crops, while agroforestry was only plantations (mostly pine or/and rubber plantations). The unequal average land area per person between SAEs and SFEs and local communities at that time became the reason for conflicts about landuse later on.

After 2005, the changes in landuse and forest coverage were driven by markets [16], particularly the markets for perennial crop products (e.g., rubber, coffee, black pepper, cashews, and fruits). The cash crop product markets strongly influenced every household in the Central Highlands, which drove farmers to change their landuse quickly and then be over-controlled by government policies; thus, all landuse plans of the government were bankrupt. Currently, coffee areas are 630,000 ha compared with 530,000 ha of government planning, and black pepper areas are 93,000 ha compared with 50,000 ha of government planning to 2025 [7]. In actuality, the government could not control the changes by any policies launched. Additionally, the population rose quickly, and within 20 years, the population increased by 44.58%, from 4.06 million persons in 1999 to 5.87 million persons in 2018 (**Figure 2**). This was combined with the expansion of agriculture (particularly perennial cash crops) following the market demands. Moreover, the market demands strongly pushed farmers to follow intensive farming practices with their cash crop cultivation, leading to higher inputs of chemical fertilizers, pesticides, and herbicides to increase crop yields. Farmers did not care about and apply agroforestry but more and more focused on mono cash crop fields. These things together resulted in negative pressures on natural forest areas. Consequently, a series of conflicts happened and continue to happen, including conflicts of landuse and management; of natural resource management (such as water and forests); of agricultural product prices; and of food safety [6].

Overall, state-owned stakeholders were leaders in destroying the natural forests with modern equipment following the assigned timber-harvesting target, but they

planted fewer trees and followed unsustainable management practices for a long time. Then, both state-owned stakeholders and farmers exploited these forests, where almost all the big timber had been harvested, to turn them into farmland. Large areas of the remaining natural forests are poor and continue to lose both their area and wealth. A series of articles reported that many natural forest areas in Gia Lai Province have been illegally cut, and although they still look like a forest from the outside, they are empty inside [2].

Forest management by the government in the Central Highlands before 2015 was a big problem with the continuous loss of forests and decreases in forest coverage [17, 18], but after 2015, the forests have been better managed, and the government has kept the forest areas (about 2.56 million ha) and forest coverage (about 46.0%) stable (**Figure 2**). Being aware of the important roles of forests, MARD kicked off a big project aimed at achieving a forest coverage of 49.2% in the Central Highlands region by 2030 [19]. The better management by the government and the unstable changes of cash crop markets have influenced and changed the farmers' awareness, leading to households shifting from mono cultivation to multi-cultivation and agroforestry, and thus, the agriculture landscape has been changing to a mosaic landscape like the agroforestry landscape as a higher approach level of ICRAF [20] and FAO [21].

3.2 The existence of agroforestry applied by the households in the central highlands

3.2.1 Agroforestry types of households

Based on the household survey data, five types of agricultural cultivation being applied by the farmers were determined, namely: (i) agroforestry mixed fruit plants, industrial plants, and woody plants (named AF1); (ii) agroforestry mixed only fruit plants or industrial plants with woody plants (named AF2); (iii) other agroforestry combinations (different from AF1 and AF2) (named AF-others); (iv) multi-cultivation mixed agricultural plants (without woody plants) (named Agr-multi); and (v) mono cultivation (only one plant type) (named Agr).

Figure 3a shows that the households applied AF1, AF2, AF-others, Agri-multi, and Agr at rates of 37.5, 20.6, 6.9, 30.6, and 4.4%, respectively. Of which, the households applying AF1 were mostly in the provinces Dak Nong, Dak Lak, Lam Dong, and Gia Lai, while households applying AF2 were mostly in the provinces Kon Tum and Gia Lai (**Figure 3b**). Analysis of the minority groups revealed that more Kinh people applied the AF1 and Agri-multi systems, while more indigenous minority people applied the AF2 system. Of note, the Agr system was applied only by the Kinh people (**Figure 3c**). Overall, at the farm level, farmers in the Central Highlands likely prefer agroforestry cultivation more than mono cash crop cultivation (about 65.0% of HHs applied agroforestry), which is a signal that farmers are approaching sustainable agriculture in the region.

3.2.2 Land areas of the households

Based on the household survey data, there are five types of land farmers use for cultivation, namely: (i) land for annual crops; (ii) perennial crops; (iii) woody crops; (iv) fish pond areas; and (v) forest land.

According to the survey data, the households had land for annual crops, perennial crops, woody crops, fish ponds, and forest land at rates of 19.4, 97.6, 6.0, 13.3,

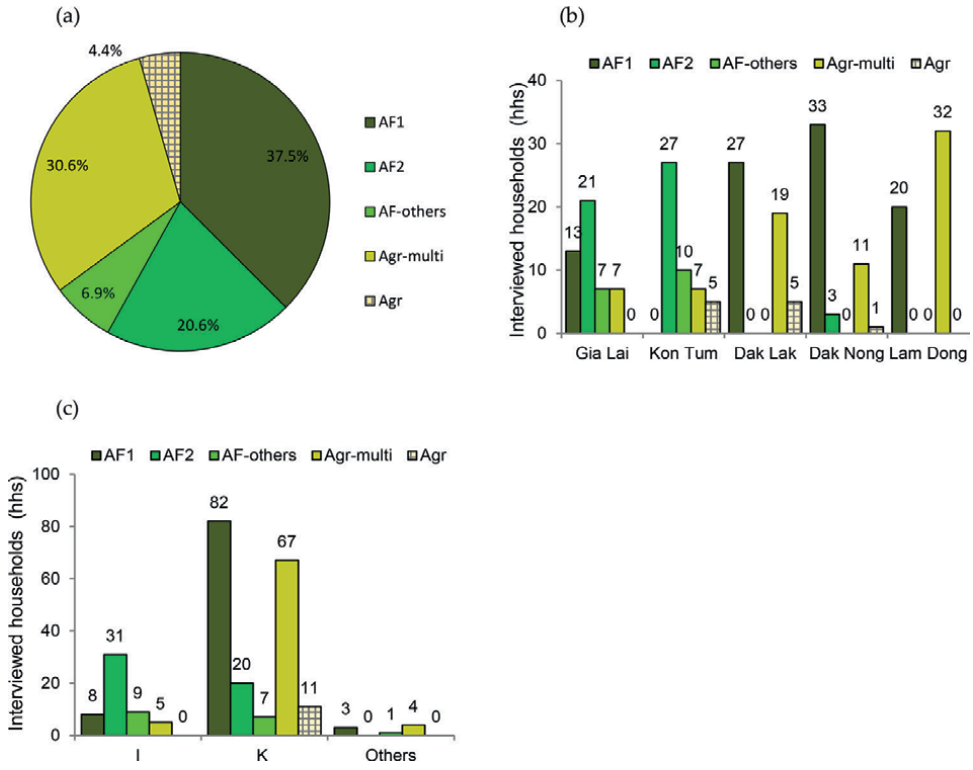


Figure 3.
Agroforestry households (HHs) at the study sites (a – Percentage of HHs applying types of cultivations; b – Number of HHs by province; c – Number of HHs by ethnic group) (Source: Surveyed data in 2018–2019) Notes: AF1 – agroforestry types including fruit, industrial, and wood trees; AF2 – agroforestry types including fruit and wood trees/industrial and wood trees; AF-others – other agroforestry types (different from AF1 and AF2); Agr – mono cultivation (only fruit tree or only industrial tree); Agr-multi – multi-cultivation (mixed fruits or/and industrial trees); I – indigenous minority groups; K – Kinh people; others – other minority groups (immigrants).

and 1.6%, respectively (**Figure 4a**). In this case, 100 could have all five types of land listed above. Almost all the households had perennial cropland, but only a few of the households had woody cropland (including plantations for wood and non-timber forest products) and forest land (mostly naturally protected forests, which households were allocated and paid to protect these forest areas). The households that had perennial cropland were distributed in all the provinces in the Central Highlands, and they preferred perennial cash crops over the others (**Figure 3b**). The minority ethnic households were twice as likely to use their land for perennial cash crops than annual crops (55/63 minority ethnic HHs had land for perennial cash crops, while only 26/63 HHs had land for annual crops). With the Kinh people, households were six times as likely to use their land for perennial cash crops than other crops (187/187 Kinh HHs had perennial cropland; 30/187 Kinh HHs had fish ponds; and 22/187 Kinh HHs had annual cropland). Households that had fish ponds were mostly Kinh people (30 Kinh HHs and 2 other minority HHs), while households that had woody land and forest land were mostly minority HHs (12 minority HHs and 3 Kinh HHs) (**Figure 4c**). Therefore, perennial cash crops appear to play an important role not only at the household level, but also at the local region level.

The average total land areas belonging to the surveyed households were different among provinces. The average land of HHs in Dak Lak, Dak Nong, Gia Lai, Kon Tum,

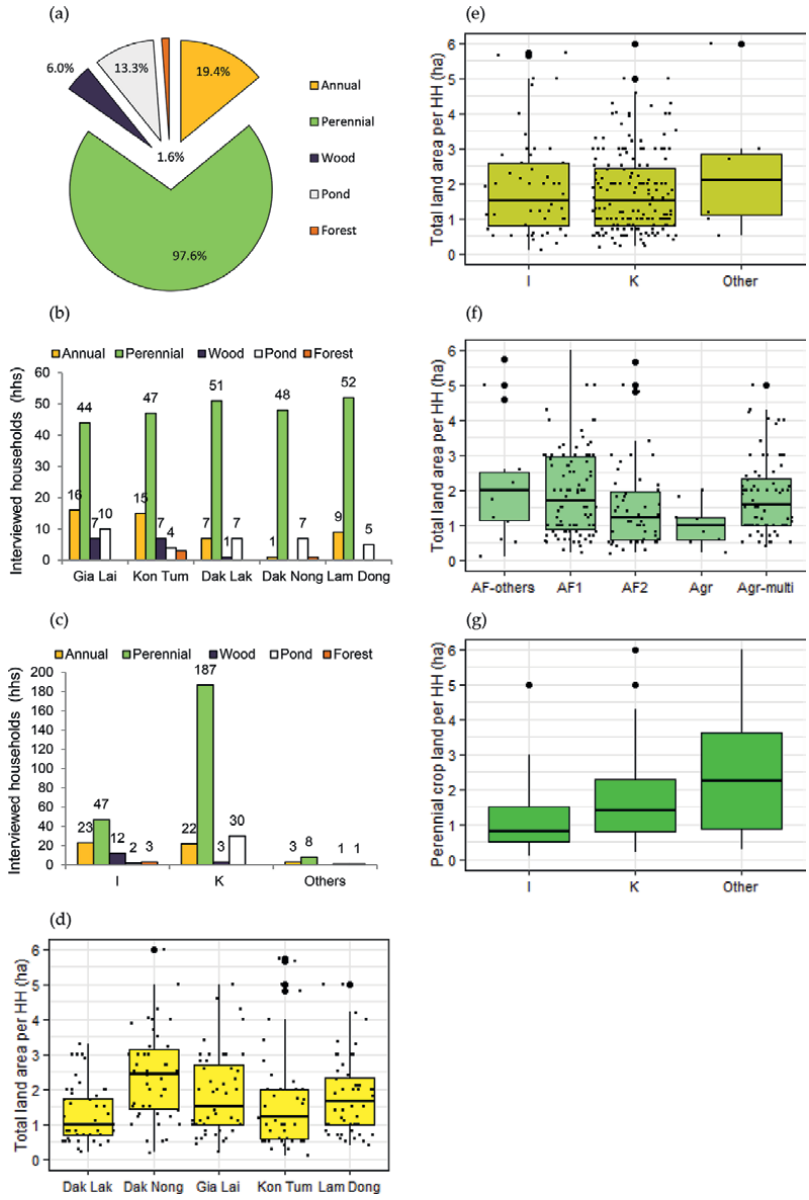


Figure 4.
Land areas of the households (HHs) at the study sites (a – Percentage of HHs with each type of land; b – Number of HHs by province; c – Number of HHs by minority groups with types of land; d – Average land area of the HHs by province; e – Average land area of the HHs by ethnic group; and f – Average land area of the HHs by types of cultivation) (Source: Surveyed data in 2018–2019) Notes: AF1 – agroforestry types including fruit, industrial, and wood trees; AF2 – agroforestry types including fruit and wood trees/industrial and wood trees; AF-others – other agroforestry types; Agr – mono cultivation; Agr-multi – multi-cultivation (mixed fruits or/and industrial trees). I – indigenous minority groups; K – Kinh people; others – other minority groups (immigrants).

and Lam Dong Provinces were 1.28 (± 0.11) ha/HH, 2.84 (± 0.34) ha/HH, 1.98 (± 0.20) ha/HH, 2.39 (± 0.38) ha/HH, and 1.82 (± 0.16) ha/HH, respectively (**Figure 4d**). Data analysis showed that the average land of the households in Dak Nong Province was higher than households in Dak Lak and Kon Tum Provinces (X^2 = 24.259, p = 7.089e^{-5}).

However, there were no differences in the average land of HHs when accounting for the HH ethnic group. The average land of the indigenous minority HHs, Kinh HHs, and other minority HHs were 1.90 (± 0.19) ha/HH, 2.06 (± 0.14) ha/HH, and 2.91 (± 0.82) ha/HH, respectively (X^2 = 1.44, p = 0.486) (**Figure 4e**). Similarly, the average land areas of HHs applying each cultivation type were not different either. The HHs applying AF1, AF2, AF-others, Agr-multi, and Agr had land areas of 2.17 (± 0.20) ha/HH, 1.66 (± 0.20) ha/HH, 3.35 (± 0.75) ha/HH, 1.81 (± 0.12) ha/HH, and 2.49 (± 1.0) ha/HH, respectively (X^2 = 8.558, p = 0.073) (**Figure 4f**). Furthermore, **Figure 4f** also presents the households that preferred to cultivate the AF1, AF2, and Agri-multi systems.

Although there were no differences in average land area among ethnic HHs, the average land for perennial crops of ethnic HHs was significantly different. The average land for perennial crops of the indigenous minority HHs, Kinh HHs, and other minority HHs were 1.17 (± 0.15) ha/HH, 1.95 (± 0.13) ha/HH, and 2.60 (± 0.77) ha/HH, respectively (X^2 = 13.49, p = 0.001176) (**Figure 4g**). Recently, the indigenous minority HHs in the Central Highlands have had the lowest perennial crop land area on record. They had more land in the past, but many of them sold their good land to Kinh and immigrant minority people.

Overall, the average land area of the households in the Central Highlands is currently higher than before 2005, as noted in the above discussion, because the Vietnamese Government applied a policy to restructure the state-owned agriculture and forest stations and then reformed them to be state-owned enterprises. Furthermore, many of the state-owned enterprises must return a large section of land to local province committees, which is then allocated to the households. In addition, many farmers have invaded and shifted the forest lands into agricultural lands based on shifting cultivation over time.

3.2.3 Land areas for agroforestry of the households

The survey results also showed that the land areas the households used for agroforestry in the Central Highlands were significantly different among ethnic groups and types of cultivation. Land areas for agroforestry of the indigenous minority, Kinh, and other minority households were 1.24 (± 0.16) ha/HH, 1.65 (± 0.11) ha/HH, and 2.7 (± 0.83) ha/HH, respectively (**Figure 5a**) (X^2 = 8.915, p = 0.01159). The land areas of households cultivating AF1, AF2, AF-others, and Agr-multi were 1.79 (± 0.15) ha/HH, 1.13 (± 0.14) ha/HH, 2.36 (± 0.74) ha/HH, and 1.49 (± 0.10) ha/HH, respectively (**Figure 5b**) (X^2 = 13.93, p = 0.00752). On average, the agroforestry land areas of the households in the study sites were very small, but many farmers were utilizing agroforestry, which is a positive sign for the future. However, the small land areas of many of the households have been an obstacle to market-based agriculture production, especially in agroforestry. Only some of the farmers surveyed had over 3 ha per household of land for agroforestry (9 households seen as the 9 big dots in **Figure 5b**), which makes it possible for these HHs to approach the market requirement.

3.3 Diversity of plants and animals in the households

3.3.1 Existence of plant and animal types in the households

The survey data showed that 96.0% of the households grew perennial industrial crops, 61.7% of the households grew fruit crops, 64.5% of the households grew woody and NTFP plants, 3.6% of the households grew medicinal plants, and 44.4% of the households raised animals and fish (**Figure 6a**).

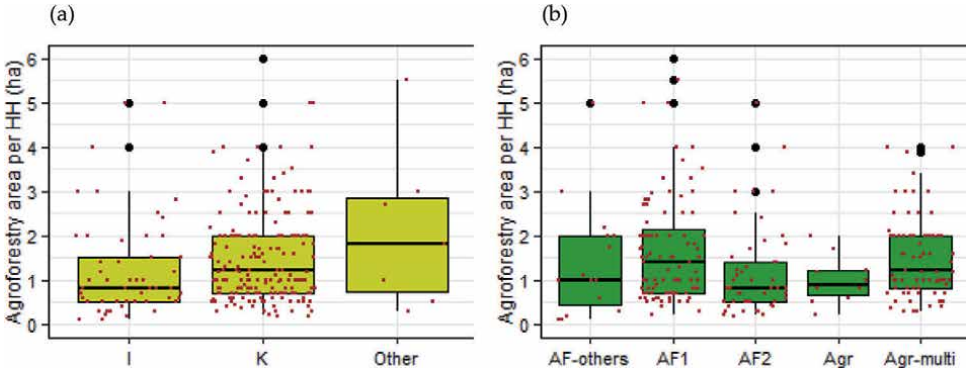


Figure 5.
Land areas for agroforestry of the households at the study sites (a – by ethnic group; b – by type of cultivation) (Source: Surveyed data in 2018–2019) Notes: AF1 – agroforestry types including fruit, industrial, and wood trees; AF2 – agroforestry types including fruit and wood trees/industrial and wood trees; AF-others – other agroforestry types (different from AF1 and AF2); Agr – mono cultivation (only fruit tree or only industrial tree); Agr-multi – multi-cultivation (mixed fruits or/and industrial trees). I – indigenous minority groups; K – Kinh people; others, other minority groups (immigrants).

Surveyed households that planted perennial industrial crops were distributed in all five provinces of the Central Highlands (45/48 HHs of Gia Lai, 47/49 HHs of Kon Tum, 48/51 HHs of Dak Lak, 48/48 HHs of Dak Nong, and 50/51 HHs of Lam Dong), while three provinces had high rates of households that planted fruit crops (Lam Dong with 51/51 HHs, Dak Lak with 45/51 HHs, and Dak Nong with 42/48 HHs), and many households also planted woody and NTFP plants in all five provinces (37/48 HHs in Gia Lai, 32/49 HHs in Kon Tum, 28/51 HHs in Dak Lak, 37/48 HHs in Dak Nong, and 26/51 HHs in Lam Dong). A few households in the region raised animals and fish (29/48 HHs in Gia Lai, 29/49 HHs in Kon Tum, 17/51 HHs in Dak Lak, 19/48 HHs in Dak Nong, and 16/51 HHs in Lam Dong) (**Figure 6b**).

Analyzed by ethnic groups, the rates of indigenous minority households growing perennial industrial crops, fruit crops, woody and NTFP plants, and medicinal plants were 48/53 HHs, 14/53 HHs, 44/53 HHs, and 10/53 HHs, respectively, and 30/53 HHs raised animals and fish; while the rates of Kinh households growing perennial industrial crops, fruit crops, woody and NTFP plants, and medical plants were 182/187 HHs, 150/187 HHs, 110/187 HHs, and 5/187 HHs, respectively, and 75/187 HHs raised animals and fish (**Figure 6c**).

3.3.2 Plant and animal diversity in agroforestry systems of the households

The research determined that there were 69 types of plants the households applied in their agroforestry systems, of which coffee, black pepper, avocado, and durian were popular choices to grow (217/248 HHs grew coffee (equivalent to 87.5%), 113/248 HHs grew black pepper (45.6%), 125/248 HHs planted avocado (50.4%), and 108/248 HHs grew durian (43.5%)). In addition, a few households also planted other crops, such as *L. glutinosa* (56/248 HHs, equivalent to 22.6%), *S. siamea* (55/248 HHs, 22,2%), jackfruit (28/248 HHs, 11,3%), and others (<10% HHs) (**Figure 7**).

Figure 8 shows the quantity of plant types grown by the households in the Central Highlands. Of which, the average number of plant types of each household applying AF-others, AF1, AF2, Agr, and Agr-multi were 3.88 (± 0.61), 5.51 (± 0.17), 2.94 (± 0.14), 2.27 (± 0.19), and 4.36 (± 0.19), respectively (**Figure 8a**) (X^2 = 91.691,

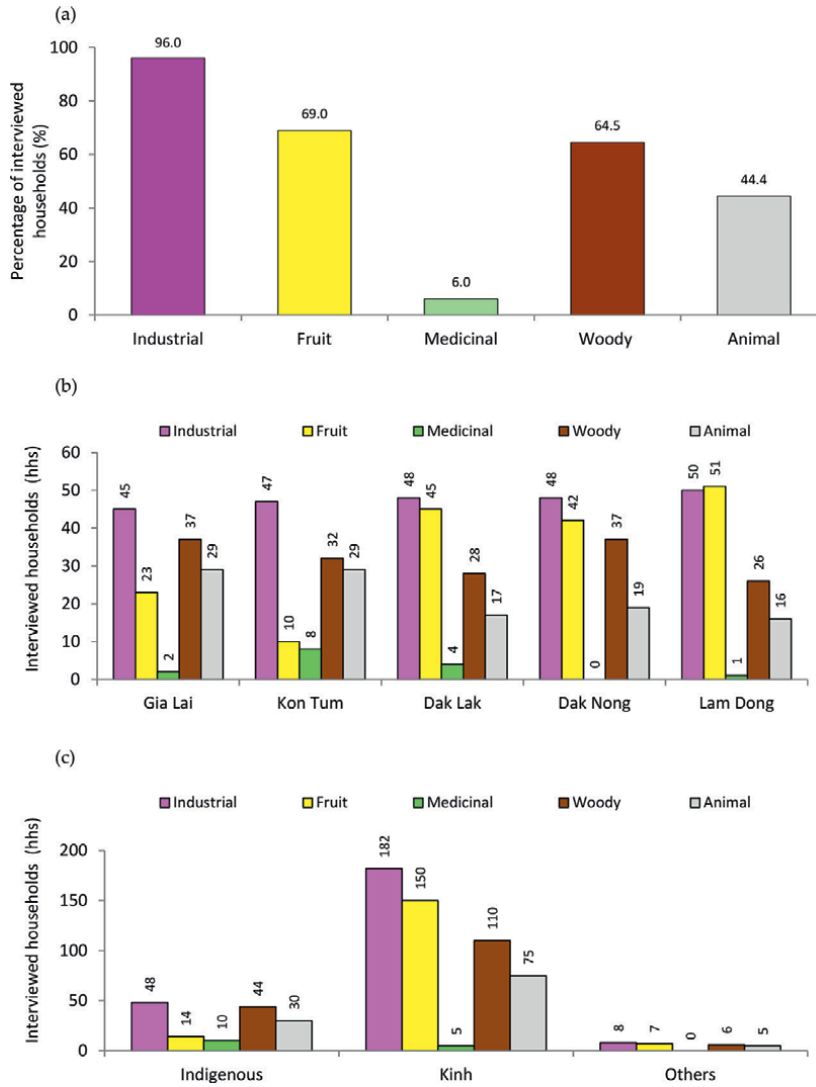


Figure 6.
Households cultivating crops and animals in their farms at the study sites (a – HHs ratio; b – by province; c – by ethnic group; Kinh is a major Vietnamese group) (Source: Surveyed data in 2018–2019).

$p = 2.2e^{-16}$). Therefore, AF1 had the most diversity in terms of types of plants used in agroforestry, allowing households to grow industrial, fruit, and wood plants together.

The plant diversity was different among households in the provinces. Households in Dak Lak, Dak Nong, Gia Lai, Kon Tum, and Lam Dong had 4.8 (± 0.26), 5.25 (± 0.25), 4.02 (± 0.31), 3.24 (± 0.2), and 4.52 (± 0.24) types of plants per household, respectively (**Figure 8b**) ($X^2 = 39.018$; $p = 6.9e^{-8}$). Thus, households in Dak Nong Province had the most diversity of plants in their agroforestry systems.

By ethnic groups, the indigenous minority households had 3.57 (± 0.20) types of plants per household, Kinh households had 4.59 (± 0.14) types of plants per household, and other minority households had 4.62 (± 0.53) types of plants per household (**Figure 8c**) ($X^2 = 11.956$, $p = 0.002534$). Thus, Kinh households had the most diversity of plants in their cultivation systems.



Figure 7.
Types of plants in agroforestry systems of the households at the study sites (a – Numbers of HHs; b – Ratio of HHs with types of plants) (Source: Surveyed data in 2018–2019).

Furthermore, the differences in plant diversity among households of ethnic groups were clearer when analyzing the types of perennial crops (including industrial, fruit, and forest plants). **Figure 8d** shows that the numbers of industrial and fruit plant types of the indigenous minority households, Kinh households, and other minority households were 2.17 (± 0.21), 3.45 (± 0.12), and 3.50 (± 0.46) types of plants per household, respectively (X^2 = 26.17; p = 2.07e^{-6}). **Figure 8e** shows that the numbers of

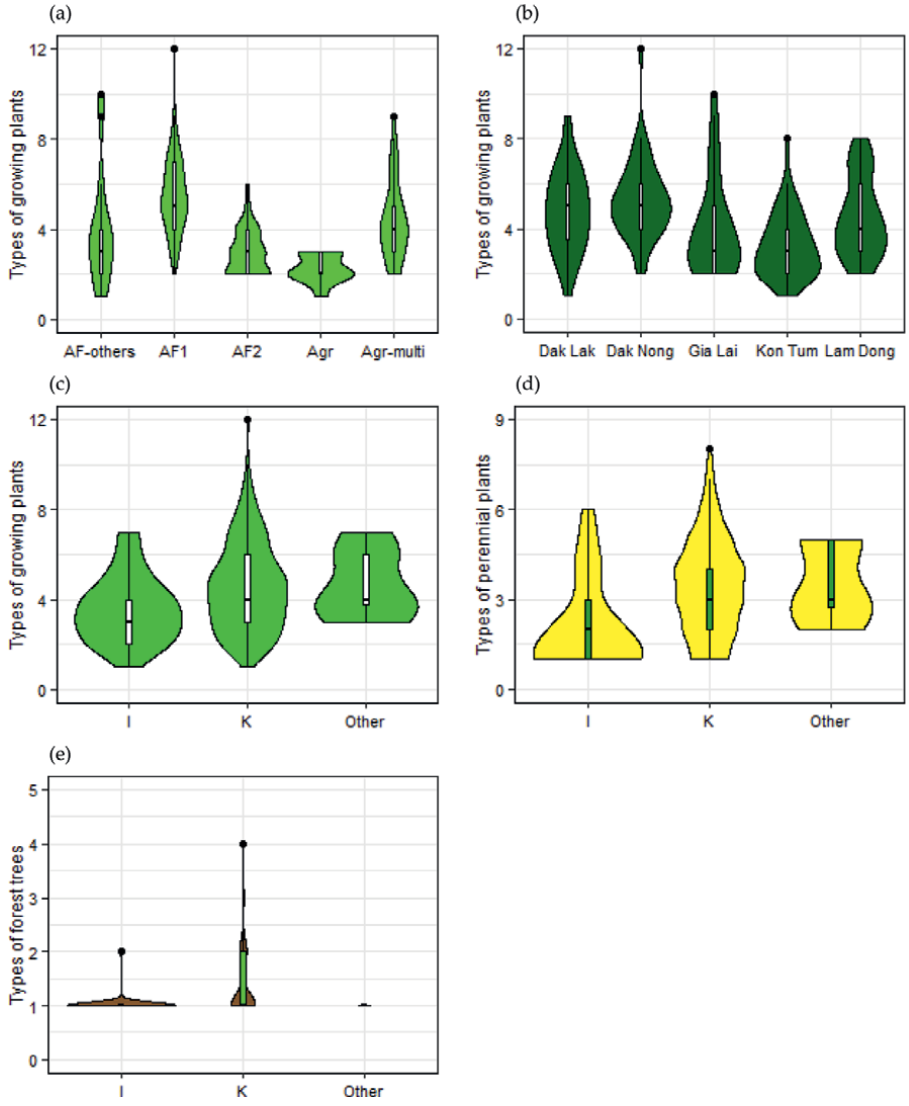


Figure 8.
Quantity of plants in agroforestry systems of households at the study sites (a – by types of cultivation; b – by provinces; c, d, and e – by ethnic groups) (Source: Surveyed data in 2018–2019) Notes: AF1 – agroforestry types including fruit, industrial, and wood trees; AF2 – agroforestry types including fruit and wood trees/industrial and wood trees; AF-others – other agroforestry types (different from AF1 and AF2); Agr – mono cultivation (only fruit tree or only industrial tree); Agr-multi – multi-cultivation (mixed fruits or/and industrial trees). I – indigenous minority groups; K – Kinh people; others – other minority groups (immigrants).

forest plant types of the indigenous minority households, Kinh households, and other minority households were 1.02 (± 0.02), 1.33 (± 0.06), and 1.0 (± 0.0) types of plants per household, respectively (X^2 = 13.837; p = 0.00098).

The research also determined that farmers in the Central Highlands have considered raising 11 major types of animals and fish, including cow, buffalo, goat, pig, chicken, swan, goose, duck, pigeon, sinkworm, and fish. Of which, the numbers of surveyed households raising chickens, cows, fish, and pigs were 56/248 HHs (equivalent to 22.6%), 45/248 HHs (18.1%), 33/248 HHs (13.3%), and 25/248 HHs (10.1%), respectively, while

other animals were raised by fewer than 10% of the surveyed households (**Figure 9a, c**). Indigenous minority households preferred to raise cows (19/53 HHs, equivalent to 35.8%) and buffalo (7/53 HHs, equivalent to 13.2%), while Kinh households tended to raise chickens (51/187 HHs, equivalent to 28.0%), fish (30/187 HHs, equivalent to 16.0%), cows (22/187 HHs, equivalent to 11.8%), and pigs (17/187 HHs, equivalent to 9.1%) (**Figure 9b**). However, raising animals was not the main activity of most of the surveyed households, so the animal-raising farms were very small.

3.4 Agroforestry perspective for future changes

Agroforestry can contribute to multi-benefits, but it is not a new cultivation or new technique with farmers in Vietnam. Agroforestry can improve soil health as it has the ability to enrich the soil's organic carbon, improve soil nutrient levels, and enhance soil microbial dynamics [22–24]. It can help keep the high yields of cash crops with suitable shade and types of trees, such as rubber [25], coffee and cacao

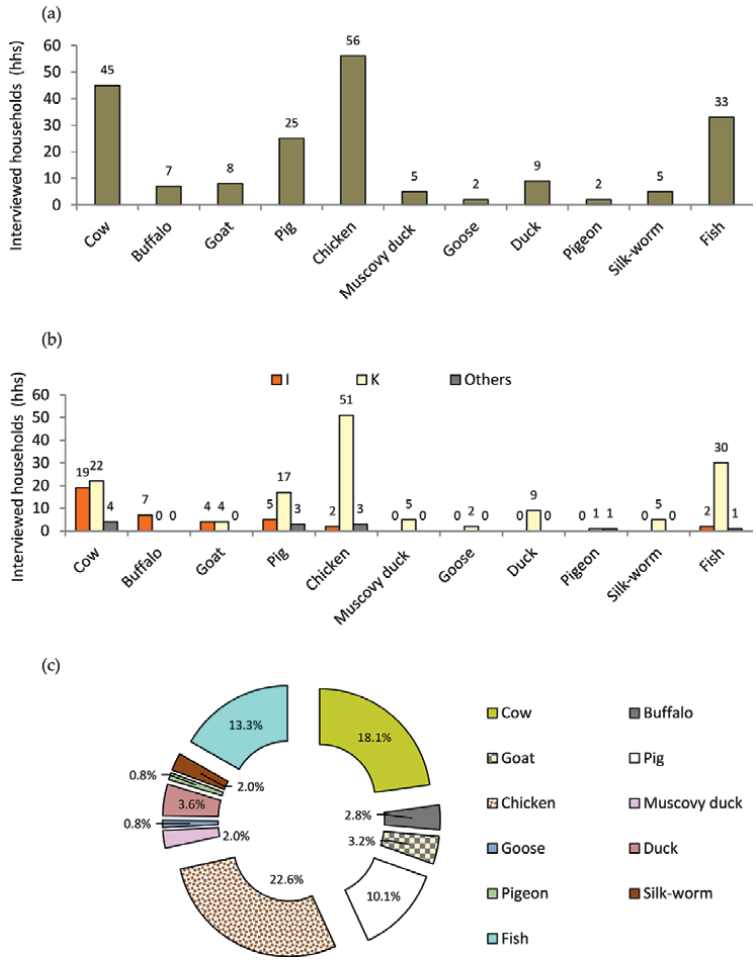
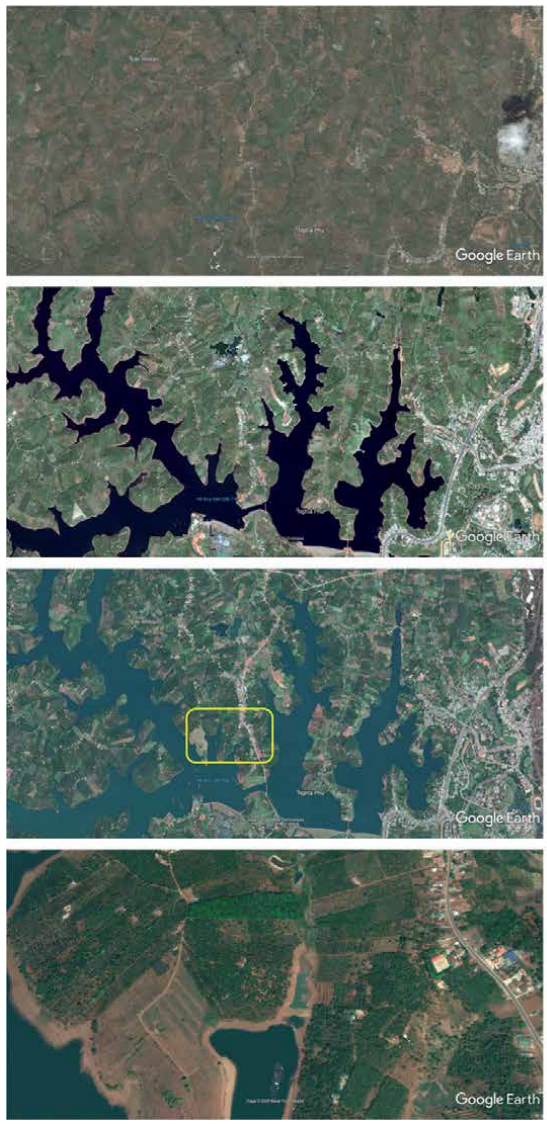


Figure 9.
Animals raised by the surveyed households at the study sites (a – number of households raising animals; b – number of ethnic households raising animals; c – Ratio of households raising animals) (Source: Surveyed data in 2018–2019) Notes: I – indigenous minority groups; K – Kinh people; others, other minority groups (immigrants).

[26–28], other crops [29], and black pepper [30]. Agroforestry can stabilize household economics and help reduce poverty [31–34] while also meeting the green market product value chain [34]. Using an agroforestry system can protect and conserve biodiversity [25, 35, 36], reduce the negative impacts of natural disasters, protect the environment [37–39], and serve other ecosystem services [35, 40–43]. It can also help land adapt to and mitigate climate change [44–46] and help in sustainable agriculture



(a) Mono agricultural based landscape
(Landsat image in 2006)

(b) Preparatory agroforestry based landscape (after Dak-tic's hydropower reservoir was completed)
(Landsat image in 2012)

(c) Agroforestry based landscape (more diverse plots with trees)
(Landsat image in 2018)

(d) Agroforestry landscape
(zooming in from the yellow area in picture c) – including trees and diverse plots of plants & cage fishery (Landsat image in 2019)

Figure 10.
An example of changing landscapes from mono agriculture expansion to agroforestry at one of the study sites (around Dak-tic's hydropower reservoir located in Gia Nghia town, Dak Nong Province) (a) mono agricultural based landscape (Landsat image in 2006); (b) preparatory agroforestry based landscape (after Dak-tic's hydropower reservoir was completed) (Landsat image in 2012); (c) agroforestry-based landscape (more diverse plots with trees) (Landsat image in 2018); (d) agroforestry landscape (zooming in from the yellow area in picture c) – Including trees and diverse plots of plants and cage fishery (Landsat image in 2019) (Source: Landsat images from Google earth free version (12°00′14″N; 107°38′24″ E)).

development [47]. In addition, agroforestry can also conserve and use local or indigenous knowledge [28].

Overall, applying multiform cultivation systems involving agroforestry and a diversity of plants and animals will be a key to sustainable agriculture development for households in the Central Highlands. Importantly, the above results also indicate that farmers have been more and more aware of applying agroforestry practices by themselves with the high diversity of cultivation, plants, and animals, which are the keys to basic agroforestry [33].

Actually, there were dozens of agroforestry systems existing traditionally and modally in the Central Highlands, which were developed by farmers themselves or introduced by scientists [48]; however, there likely exist unclear obstacles to allowing agroforestry to be expanded. The total agroforestry area in Vietnam was estimated by ICRAF to be about 900,000 ha, and 10 million ha were identified as being suitable for agroforestry [49]. Moreover, further work by ICRAF continues to bring evidence to policy dialogs, including assessing the possible roles of agroforestry for Vietnam targets to international conventions, such as the Nationally Determined Contributions [45]. At the global level, many symposia have brought together agroforestry researchers, academicians, planners, policymakers, and administrators to discuss agroforestry research for sustainable development and to address future scenarios [46].

Traditionally, agroforestry was similar to circular agriculture and local organic and/or ecological agriculture at the household level by itself. However, under higher market demands, agroforestry in Vietnam must be upgraded to a higher level – a landscape agroforestry level, which ICRAF has been developing. Agroforestry in some places has already been moving to a landscape level (**Figure 10**). The landscape agroforestry level can not only cope with the requirement of market-based production, but can also provide basic roles and multi-benefits. Agroforestry can be a key aspect to develop an agricultural circular economy.

Therefore, to conserve forest areas and coverage, transform the lives of rural farming populations, protect ecosystems, and ensure food/fodder security through a sustainable basis in the Central Highlands and the whole of Vietnam, a National Agroforestry Policy will be a path-breaker as a legal instrument for making agroforestry a compulsory application. In addition, the technical guides for agroforestry at both the farm and landscape levels will also be launched together with the policy to approach the market-based production of cash crops.

4. Conclusion

Agriculture expansion in the Central Highlands of Vietnam during the period from 1999 to 2018 was closely connected with forest degradation. In 1999, the total forest land was 2.99 million ha, with forest coverage of 56.8%, while agricultural land was 1.23 million ha. In 2018, the total forest land was 2.56 million ha, with forest coverage of 46.0%, while agricultural land was 2.43 million ha.

The percentages of surveyed households applying AF1, AF2, AF-others, Agri-multi, and Agr were 37.5, 20.6, 6.9, 30.6, and 4.4%, respectively. The average land areas of HHs in Dak Lak, Dak Nong, Gia Lai, Kon Tum, and Lam Dong Provinces were 1.28 (± 0.11) ha/HH, 2.84 (± 0.34) ha/HH, 1.98 (± 0.20) ha/HH, 2.39 (± 0.38) ha/HH, and 1.82 (± 0.16) ha/HH), respectively. The average land areas of the indigenous minority HHs, Kinh HHs, and other minority HHs were 1.90 (± 0.19) ha/HH, 2.06 (± 0.14) ha/HH, and 2.91 (± 0.82) ha/HH, respectively. The average land areas of

households applying AF1, AF2, AF-others, Agr-multi, and Agr were 2.17 (± 0.20) ha/HH, 1.66 (± 0.20) ha/HH, 3.35 (± 0.75) ha/HH, 1.81 (± 0.12) ha/HH, and 2.49 (± 1.0) ha/HH, respectively.

Agroforestry at both the farm and landscape levels existed in the region and featured diversity. There were 69 types of plants and 11 major types of animals and fish the households applied in their agroforestry systems, of which coffee, black pepper, avocado, and durian were popular choices to grow.

We recommended that a National Agroforestry Policy and technical guides for agroforestry at both the farm and landscape levels should be launched together to approach the market-based productions of cash crops, and circular agriculture development.

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Competing interests

The authors declare that they have no competing interests.

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This book, *Sustainable Forest Management - Surpassing Climate Change and Land Degradation*, is devoted to important issues forest managers face. Besides managing forest resources, the issues addressed include aspects of climate change, biodiversity conservation, and agroforestry. The book contains four sections, each devoted to this set of topics. Forest management is very important in the context of sustainable use of resources. To achieve this, forest management should aim at improving economic profitability for the investors, preserve the ecosystem structure to serve society, and maintain all (physical, economic, social, and other) ecosystem functions. All these aspects of forest management have been addressed in various chapters of this book. The editor sincerely hopes this will be a welcome addition to the field of forest management.

J. Kevin Summers, Environmental Sceinces Series Editor

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