

**VEGETATION AND FOREST CARBON DYNAMICS IN RELATION
TO ANTHROPOGENIC IMPACTS AND CLIMATE VARIABILITY AT
SELECTED SITES IN INDIA**

by

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(2019-20-004)

THESIS

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COLLEGE OF CLIMATE CHANGE AND ENVIRONMENTAL SCIENCE

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2024

DECLARATION

I, hereby declare that the thesis entitled "**VEGETATION AND FOREST CARBON DYNAMICS IN RELATION TO ANTHROPOGENIC IMPACTS AND CLIMATE VARIABILITY AT SELECTED SITES IN INDIA**" is a bonafide record of research work done by me during the course of research and the thesis has not been previously formed the basis for the award to me of any degree, diploma, fellowship or other similar title, of any other University or Society.

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Certified that the thesis entitled "**VEGETATION AND FOREST CARBON DYNAMICS IN RELATION TO ANTHROPOGENIC IMPACTS AND CLIMATE VARIABILITY AT SELECTED SITES IN INDIA**" is a record of research work done independently by Ms. Swedha P Sudevan under my guidance and supervision and it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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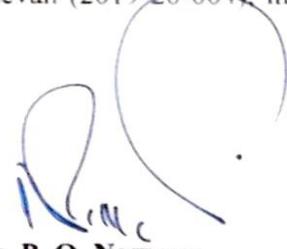
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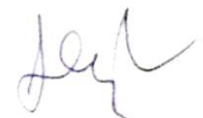
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Abbreviations

1. IPCC – Intergovernmental Panel on Climate Change
2. NR – Natural Rubber
3. NDVI - Normalized Difference Vegetation Index
4. AGB – Above Ground Biomass
5. IBH – Indo Burma Biodiversity Hotspot
6. DEMs - Digital elevation models
7. PWS – Pualreng Wildlife Sanctuary
8. FCC – False Colour Composite
9. NCC – Natural Colour Composite
10. FSI – Forest Survey of India
11. ISFR - India State of Forest Report
12. LULC - Land Use and Land Cover
13. QGIS - Quantum Geographic Information System
14. CRISP – Comprehensive Rubber Information System Portal
15. AGC – Above Ground Carbon
16. GA – Geographical Area
17. SRTM - Shuttle Radar Topography Mission
18. PA – Protected Area
19. SDGs – Sustainable Development Goals
20. USGS - US Geological Survey
21. SoI – Survey of India
22. VDF - Very Dense Forest
23. MDF - Moderately Dense Forest
24. OF – Open Forest
25. WRIS - Water Resource Information System

CHAPTER-1

INTRODUCTION

Forests and vegetation play a vital role in sustaining ecosystem stability, securing food supplies, and improving environmental conditions for all forms of life. Therefore, it is crucial to track the health of global forests and biodiversity, observe how they evolve over time, and understand the effects of climate change (Bhatt et al., 2022). Forests worldwide have been heavily exploited for resources, and the increasing demand has led to unsustainable use rather than conservation. Focused research on vegetation and forest dynamics is necessary to preserve biodiversity and maintain the functionality of forests for the sustenance of human life.

India, with its diverse climatic, soil, and topographical conditions, boasts a wide range of natural vegetation, from rainforests in the Western Ghats and Eastern Himalayas to deserts in Rajasthan (Singh et al., 2022). Forests globally cover 31% of the Earth's land area, harbour between 2 million and 1 trillion species, and provide habitats for 80% of amphibian species, 75% of bird species, and 68% of mammalian species. Deforestation significantly contributes to forest loss, with the Asia-Pacific region experiencing a reduction of 4.7 million hectares from 2010 to 2020 and a global loss of 13 million hectares between 2000 and 2010.

Human activities have significantly contributed to the decline and loss of plant, animal, and microbial species. Factors such as deforestation, intensive land use, inadequate forest management, agricultural expansion, encroachment, slash-and-burn techniques, forest fires, urbanization, overharvesting, and overall environmental degradation are primary drivers of this loss. Since 1751, over 1.5 trillion tonnes of CO₂ have been emitted globally, underscoring the urgent need to conserve biodiversity in human-altered environments to maintain ecosystem services and support conservation efforts (Bhatt et al., 2022).

1.1 Forest carbon dynamics

Forested ecosystems, which constitute the largest terrestrial sink for atmospheric CO₂, play a crucial role in the global carbon cycle. Understanding the mechanisms behind long-term trends and the annual-to-decadal variability in forest carbon sink strength is essential for reducing uncertainties about future atmospheric greenhouse gas levels and global temperatures. This knowledge has significant social and economic policy implications (<https://huh.harvard.edu/>).

The carbon stored in forest ecosystems is a vital component of the global carbon cycle. Forest carbon dynamics significantly impact atmospheric CO₂ concentrations and carbon neutrality goals by either capturing or releasing CO₂ (<https://www.frontiersin.org/>). Between 1990 and 2007, forest ecosystems globally sequestered approximately 2.4 ± 0.4 petagrams (Pg) of carbon per year. On average, forests can accumulate 3.58 megagrams (Mg) of carbon per hectare annually (Pan et al., 2021).

1.2 Anthropogenic impacts on forest and vegetation

Human activities have profoundly transformed forests, putting pressure on species, fragmenting wildlife populations, altering habitats, introducing non-native pests and competitors, and domesticating various species. These changes have affected genetic diversity within and among species by disrupting evolutionary processes, including habitat destruction, selective pressures, genetic implications, gene flow, and species transformation (Batt et al., 2022).

Deforestation is a major contributor to rising greenhouse gas emissions because forests play a crucial role in removing CO₂ from the atmosphere (Batt et al., 2022). Without immediate and substantial emission reductions across all sectors, limiting global warming to 1.5°C will be unattainable (IPCC, 2022). Deforestation, particularly in tropical forests, is more severe than ever (CDP, 2019). Logging has an outsized impact on deforestation (Rudel et al., 2000). Tropical deforestation is driven by a complex array of social, ecological, economic, environmental, and biophysical factors, which differ by region, country, and locality. Economic elements such as taxation policies, subsidies, corruption, and property rights are often more closely associated with deforestation than factors like population growth or density. Furthermore, cultural and sociopolitical issues, such as insufficient public support for forest conservation and sustainable management, significantly contribute to deforestation (Batt et al., 2022).

Urban expansion and infrastructure development lead to forest fragmentation (Ledig et al., 1992). This fragmentation disrupts global forest biodiversity, impairs ecosystem functions, and undermines ecosystem services, posing a threat to the long-term health and resilience of forest ecosystems. In recent decades, tropical forests have experienced unparalleled losses due to agricultural activities, logging, and urban sprawl (Lewis et al., 2015). Grazing is another factor responsible for forest and vegetation loss, particularly where traditional forest management practices are employed. Agriculture is responsible for around 80% of global

deforestation, while the remaining deforestation is attributed to infrastructure development, mining, and urban expansion (FAO, 2020). Drylands, characterized by inconsistent rainfall and low soil fertility, are especially susceptible to land degradation from activities such as ploughing, grazing, deforestation, and inadequate land management (McSweeney, 2019). Additionally, forest fires contribute to global greenhouse gas emissions and can negatively impact human health.

While fires are a natural part of boreal forest dynamics, they are predominantly human-induced in the humid tropics (Tyukavina et al., 2022).

Poor forest management is a key factor in the negative human impact on urban and suburban forests (Pedrotti et al., 2013). Environmental degradation, caused by industrial and urban emissions and pollutants such as sulphur dioxide, ozone, nitrogen oxides, particulate matter (PM₁₀ and PM_{2.5}), and soil contaminants (heavy metals and acid deposition), also contributes to the decline of forest vegetation and its adverse effects on human health and biodiversity (Ledig et al., 1992).

1.3 Above-Ground Biomass (AGB) and Carbon Stock

The Above-Ground Biomass (AGB) of a forest ecosystem is a crucial parameter for understanding its functionality. Studying forest and vegetation biomass is crucial for understanding carbon storage in key tree components and for assessing carbon cycling at regional and global scales (Behera et al., 2017). In tropical forest ecosystems, major carbon pools include the living biomass of trees, understory vegetation, and deadwood—both standing and fallen, as well as woody debris and soil organic matter. Of these, the Above Ground Biomass (AGB) of trees represents the largest carbon pool and is directly affected by deforestation and forest degradation (Gibbs et al., 2007). Changes in forest area and biomass due to management practices and regrowth have a significant impact on carbon transfer between terrestrial forests and the atmosphere (Houghton et al., 2005). Thus, accurately estimating forest carbon stocks is essential for evaluating the scale of carbon exchange between forests and the atmosphere. This estimation helps quantify the amount of carbon emitted when forests are deforested or degraded and provides insights into current and future carbon stock statuses (Houghton et al., 2005).

The IPCC (Eggleston et al., 2006) identifies five carbon pools in terrestrial ecosystems related to biomass: above-ground biomass, below-ground biomass, dead litter, woody debris, and soil organic matter. Carbon dioxide captured by plants through photosynthesis moves

among these various carbon pools. The above-ground biomass of trees constitutes the largest segment of the carbon pool and is the most prominent and noticeable component of terrestrial forest ecosystems (Ravindranath et al., 2008). Land use changes such as forest degradation and deforestation directly impact this carbon pool component.

Evaluating the biomass concentrated in forest ecosystems is vital for understanding their productivity and sustainability. This assessment also helps estimate the potential carbon dioxide emissions resulting from forest clearing or burning. By estimating forest biomass, we can gauge the amount of carbon dioxide sequestered from the atmosphere by the forest. Precise biomass measurements are essential for various applications, including timber extraction, tracking changes in forest carbon stocks, and analysing the global carbon cycle. Forest biomass can be measured using field surveys, remote sensing technologies, and GIS methods (Lu et al., 2006).

1.4 Climate variability influence on vegetation and forest ecosystem

Climate change is one of the most significant global challenges, profoundly impacting forest ecosystems. Forests are highly sensitive to climate variations, which affect species distributions, growth rates, and forest structures. Climate change influences forest ecosystems by altering tree growth, mortality, and reproduction. Rising temperatures cause earlier bud burst, leafing, and flowering in trees, directly affecting plant photosynthesis and respiration, and indirectly increasing infestation risks. Climate change also modifies disturbance regimes, impacting the carbon cycle, forest structure, and species composition, leading to disruptions from fires, species invasions, and insect and disease outbreaks. Fire disturbances in forest ecosystems can disrupt wildlife habitats, accelerate nutrient cycling, and cause tree mortality, with the frequency, size, intensity, seasonality, and type of fires influenced by precipitation patterns and forest composition (Gebeyehu and Hirpo, 2019).

Climate is the primary force shaping major biomes such as forests and grasslands (LSMOH, 2012). Currently, global climate change is marked by rising temperatures, increased atmospheric carbon dioxide levels, and altered precipitation patterns. These changes affect host physiology and defences, pest relationships, and interactions with other species, such as natural enemies, competitors, and mutualists (Moore and Allard, 2008). Warmer temperatures cause earlier phenological events in trees, although this varies year to year and regionally, and increase infestation risks (Zhu, 2018). Climate change's impact on forest ecosystems is primarily related to carbon emissions and sequestration. Increased disturbance severity could

drastically affect forest structure, species composition, and their role as carbon sinks (Battles et al., 2008).

Climate change significantly influences forest growth, community composition, and species distribution ranges, affecting forest production and carbon storage potential (Wu et al., 2020). Forests are crucial for carbon storage and mitigating global climate change (IPCC, 2013). Future climate change, driven by rising greenhouse gases, could complexly impact forest carbon balance. Studies show that warming leads to higher soil respiration and Soil Organic Carbon (SOC) loss (Bronson et al., 2008).

In India, climate change research frequently concentrates only on climatic factors. In southern high-altitude areas, both climate and vegetation have reacted to historical global climate changes (Rajagopalan et al., 1997). Mountain forests are especially susceptible to the impacts of climate change (Gopalakrishnan et al., 2011). Rainfall significantly affects forest cover development and, consequently, the environment (Tiwari, 2006), underscoring the need to incorporate climate change considerations into long-term forest management plans (Ravindranath et al., 2006).

In India, monsoon precipitation and land surface temperature play crucial roles in determining vegetation distribution (Sarkar and Kafatos, 2004). Vegetation depends on moisture, rainfall, and suitable temperatures, which are influenced by regional weather conditions. For analysing extensive vegetated areas, the Normalized Difference Vegetation Index (NDVI) is an effective method, allowing the use of historical or current images even without ground truth data (Chandrabose et al., 2012). Changes in vegetation and land use/land cover are closely associated with seasonal variations in precipitation, which in turn impact regional climate. Aerosols influence carbon uptake and transpiration once sunlight reaches vegetation. Additionally, shifts in rainfall and temperature patterns, along with rising atmospheric CO₂ levels due to human activities, are driving climate change (Palmate et al., 2017).

1.5 Rubber cultivation - an overview

Rubber plantation is the second largest tropical plantation ecosystem after oil palm, planted for their substantial economic value and notable carbon sequestration capacity, contributing significantly to economic development and ecosystem services (Li et al., 2022). As economic globalization progresses, the importance of rubber products in the national

economy is increasing, leading to a growing demand for natural rubber and an expanding area of rubber plantations (Ye et al., 2018).

Rubber is a crucial agricultural crop in the tropics, rapidly expanding into both optimal and sub-optimal climates in nearly all rubber-growing countries worldwide. To accommodate rubber plantations, large areas of natural forests, degraded forests, and other crops have been cleared, making rubber one of the most widespread smallholder tree crops. In Kerala, rubber is a major commercial crop, covering 21% of the total cropped area and ranking second only to coconut. The area under rubber cultivation expanded from 100,000 hectares in 1957-58 to 548,000 hectares in 2013-14, with rubber plantations occupying 14% of Kerala's total geographical area. Originally native to the Amazon basin, rubber was introduced to tropical Asia as a plantation crop in the late 19th century (<http://rubberboard.org.in>). It has a plantation cycle of 25-30 years and takes 5-6 years from planting to reach maturity. Unlike other plantations, rubber offers distinctive vegetative cover and is cultivated both as a large-scale estate crop, replacing forest vegetation, and as smallholdings, replacing food crops. Rubber plantations have played a significant role in socio-economic development and boosting per capita income (Chattopadhyay, 2021).

In 1960-61, Kottayam district held 36% of Kerala's total rubber plantation area. By 2013-14, this share had decreased to 21%, with Ernakulam at 11% and Pathanamthitta at 9%. Alappuzha had less than 1%, and Wayanad approximately 2%. In 2013-14, the combined rubber plantation areas of the southern districts-Thiruvananthapuram, Kollam, Pathanamthitta, Kottayam, Idukki, and Ernakulam accounted for 61% of Kerala's rubber plantations, a decrease from 73% in 1991-92 (Chattopadhyay, 2021).

Rubber grows best in regions that were originally tropical rainforests, at altitudes below 400 meters, with temperatures between 21°C and 35°C and annual rainfall of about 200 cm. It thrives in deep, well-drained soils and prefers areas without a pronounced dry season. Since 2012, rubber plantations in India have increased by 722,000 acres (Pradeep et al., 2020).

To understand the impacts of land use and land cover changes on carbon and water cycles, mapping and monitoring the spatial and temporal dynamics of rubber plantations is crucial (Li & Fox, 2011). Geospatial technology plays a key role in quickly assessing rubber plantations, determining their ages, and differentiating them from other types of vegetation due to their unique leaf phenology. Recently, Earth Observation (EO) data has been extensively used to map monoculture plantations such as rubber, mangroves, tea, and coconut (Koedsin

and Huete, 2015). Research indicates that remote sensing technology provides a cost-effective method for covering large areas and helps in understanding plantation dynamics and stand ages compared to traditional survey techniques (Cui et al., 2022; Perumal & Bhaskaran, 2010). The distinctive phenology of natural rubber, identified through time series data from the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), aids in distinguishing rubber from other types of vegetation (Pasha et al., 2023).

1.6 Natural rubber plantations-properties and uses

Natural Rubber (NR) is the most versatile industrial raw material of plant origin, primarily sourced from the rubber tree *Hevea brasiliensis*, native to the Amazon River basin. Introduced to tropical Asia and Africa by the British Government in the late 19th century, the rubber tree thrives in diverse agro-climates and soil conditions, provided there is well-distributed annual rainfall of about 200 cm. The economically valuable latex is harvested through a process called tapping, where controlled wounding of the tree bark allows the latex to flow out for collection.

Latex comprises up to 40% natural rubber, with the remainder being water and other constituents. Natural rubber is a high molecular weight polymeric substance exhibiting visco-elastic properties, structurally identified as *cis* 1,4-polyisoprene. Isoprene, a diene, forms a double bond in each of its units in the polymer, resulting in natural rubber's reactivity as an unsaturated polymer. It can form additional compounds with halogens, ozone, hydrogen chloride, and other olefin-reactive substances. A notable reaction of natural rubber is vulcanization, where it combines with sulphur. This process transforms raw rubber's plastic and viscous nature into an elastic material. Vulcanized rubber boasts high tensile strength, reduced elongation, and superior hardness and abrasion resistance compared to raw rubber. These unique properties make natural rubber indispensable in manufacturing a wide array of products (<http://rubberboard.org.in/>).

1.7 Annual Trends in the area of natural rubber in India

The rubber board of India provided the annual trends in the area of natural rubber and tappable rubber in hectares from the year 2005 to 2023.

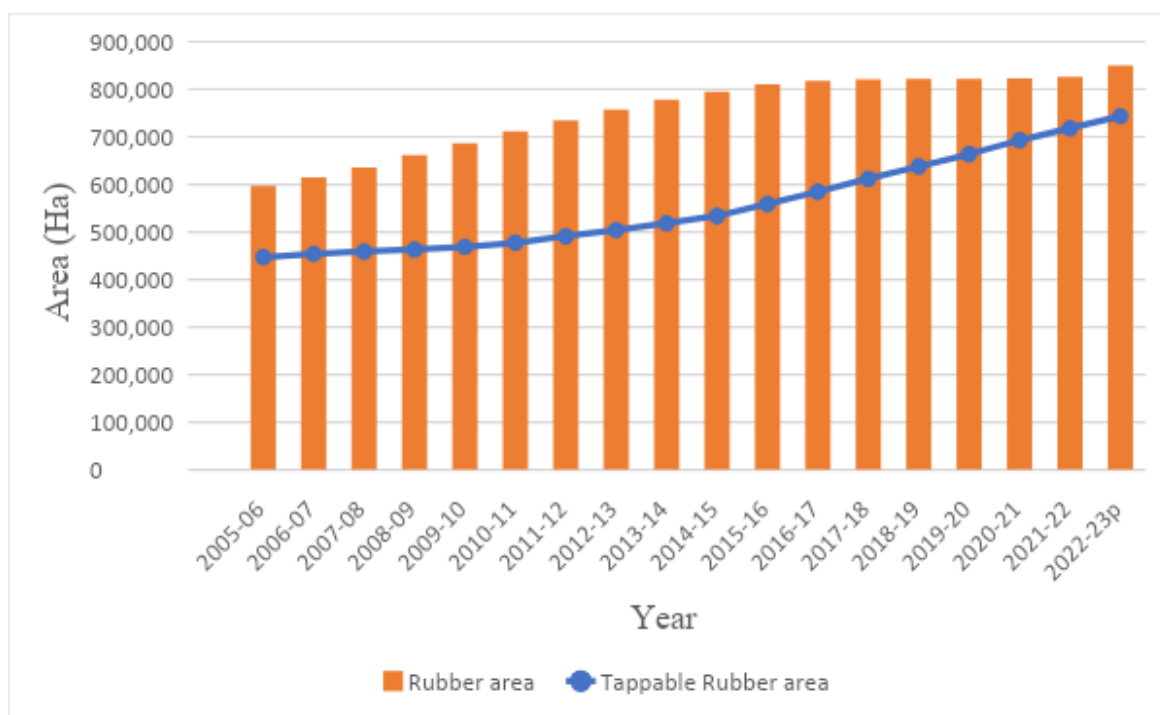


Figure 1: Graph showing the trend in rubber area in India (Source: <http://rubberboard.org.in>)

1.8 Forest cover in India

The Forest Survey of India (FSI) defines forest cover as any land area exceeding 1 hectare with a tree canopy density of more than 10 percent. The Indian State of Forest Report (ISFR) does not distinguish between natural and artificial tree crops or specific tree species, and it encompasses all land types regardless of their ownership, usage, or legal classification. This definition includes a variety of tree species such as bamboo, fruit trees, and coconut palms, as well as all land types whether they are forested, private, community, government, or institutional that meet the specified criteria (<https://fsi.nic.in/isfr-2021/>).

Forest cover in the country is categorized into three density classes: very dense forest (VDF), moderately dense forest (MDF), and open forest (OF). In addition to these categories, scrub areas are also identified and mapped, though they are not included in the forest cover classification.

The total forest cover in India, according to the current assessment, is 713,789 km², making up 21.71 percent of the nation's total geographical area. The area covered by VDF is 99,779 km² (3.04 percent), MDF is 306,890 km² (9.33 percent), and OF is 307,120 km² (9.34 percent). Together, very dense and moderately dense forests constitute 57 percent of India's total forest cover (<https://fsi.nic.in>).

Table 1: The table represents the forest cover in India (Source: FSI, 2021)

(in sq.km)

Class	Total Area	Geographical Area (%)
Very Dense Forest	99,779	3.04
Moderately Dense Forest	3,06,890	9.33
Open Forest	3,07,120	9.34
Total Forest Cover	7,13,789	21.71
Scrub	46,539	1.42
Non-Forest	25,27,141	76.87
Total Geographical Area	32,87,469	100

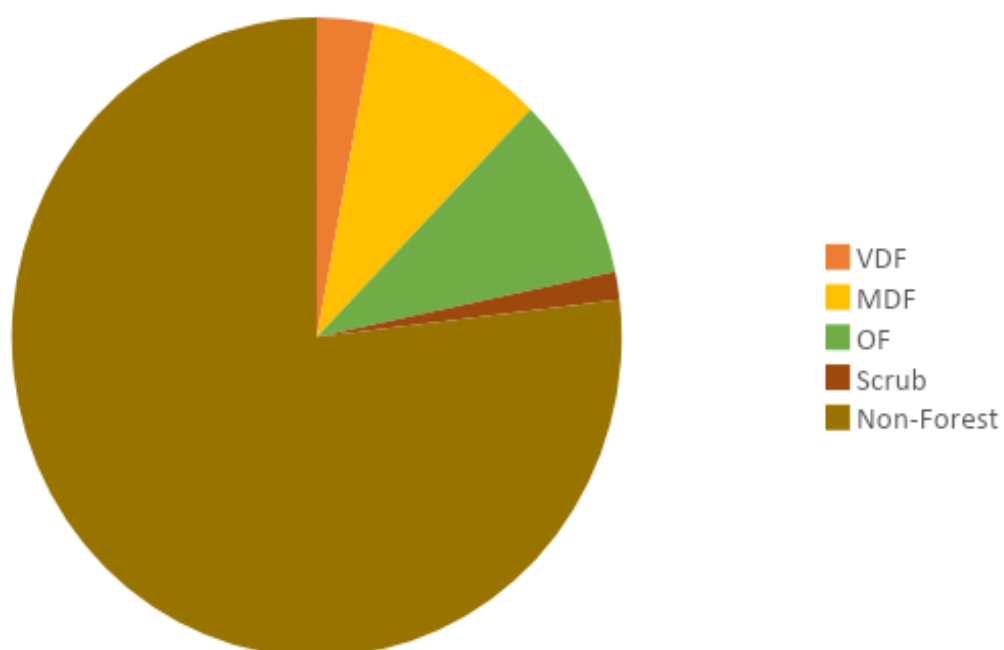


Figure 2: Percentage of forest cover in India (Source: FSI, 2021)

1.9 Protected area network in the country

In India a total of 998 protected areas are there covering 173629.52 sq. km area which is 5.28% coverage in the country. Among 998 PA, there are 106 national parks, 567 wildlife sanctuaries, 105 conservation reserves and 220 community reserves. India's forest cover as per

the (FSI, 2021) report is 24.62% of the total geographical area of the country which includes 21.71% of the forest and 2.91 % of the tree cover (<https://vanagniportal>).

1.10 Indo Burma Biodiversity Hotspot

Indo-Burma is considered one of the top 10 biodiversity hotspots for irreplaceability and ranks among the top five for threat levels, due to its high plant and animal endemism and the limited extent of its natural habitats. It is the most densely populated hotspot, with its remaining natural ecosystems-already significantly reduced-facing severe and increasing pressures from habitat loss, degradation, fragmentation, and over-exploitation of natural resources.

According to IUCN reports, only 5% of the region's native habitat remains which make it very endangered. More than any other hotspot, the Indo-Burma hotspot has a sizable human population which intensified the problems the area faces (<https://www.iucn.org>). The Indo-Burma Biodiversity Hotspot is one of the world's most crucial biological regions. Around 15,000 plant species, 1,300 bird species, 1,200 animal species, and 400 reptile species can be found there. It is home to many endemic species as well as certain endangered species, including the saola, the Asian elephant, the tiger, and the rhinoceros (Stephen et al., 2015).

The Indo-Burma biodiversity hotspot opposes major threats and challenges regardless of its ecological importance. The increased human activities in these areas caused high habitat loss and fragmentation. As a result of this, the hotspot's habitats have degenerated, and critical natural resources have been lost. The lack of information on the species found in the Indo-Burma region further emphasizes the need for more studies or research and conservation initiatives (Huang et al., 2021).

1.11 Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is one of the earliest remote sensing analytical tools designed to simplify the complexities of multi-spectral imagery. It has become the most popular index for vegetation assessment. Its widespread use is due to the fact that NDVI can be calculated with any multispectral sensor that has both visible and near-IR bands (Huang et al., 2021). Proposed by (Kriegler et al., 1969), NDVI is a simple band transformation where the difference between near-infrared (NIR) radiation and red radiation is divided by their sum, resulting in a simplified image known as the Normalized Difference Vegetation Index. Mathematically, NDVI is expressed as follows:

NDVI is calculated using the formula:

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$$

where NDVI stands for Normalized Difference Vegetation Index. Red and NIR represent the spectral radiance (or reflectance) measurements recorded by sensors in the red (visible) and near-infrared (NIR) regions, respectively (Huang et al., 2021).

1.12 Digital Elevation Model

A Digital Elevation Model (DEM) is a representation of the bare ground topographic surface of the Earth, excluding trees, buildings, and other surface objects (<https://www.usgs.gov>). Digital topography, expressed as a DEM, is widely used across various disciplines, including geomorphometry, cryosphere and soil sciences, precision agriculture, defence, sports, tourism, telecommunications, land planning, hydrology, natural hazards, remote sensing, and even video games. Ideally, DEMs capture the interface between the atmosphere and the lithosphere using a discrete two-dimensional grid, though complexities arise from interactions with the hydrosphere, cryosphere, biosphere, and anthroposphere. The treatment of DEM surfaces, influenced by these intervening spheres, depends on their intended use and the characteristics of the sensors used to create them (Guth et al., 2021).

1.13 Objectives of the study

1. Understanding forest carbon stock dynamics with multi-source data integration.
2. Assessing the impact of human activities and climate on forest carbon pool.

CHAPTER-2

REVIEW OF LITERATURE

IPCC Volume 4 provides guidance for preparing annual greenhouse gas inventories in the Agriculture, Forestry, and Other Land Use (AFOLU) sector. This volume integrates the previously separate guidance from the 1996 IPCC Guidelines for National Greenhouse Gas Inventories for Agriculture (Chapter 4) and Land Use, Land-Use Change, and Forestry (Chapter 5). This integration acknowledges that greenhouse gas emissions and removals, as well as various forms of terrestrial carbon stocks, can occur across all types of land, with practices often influencing both Agriculture and Land Use, Land-Use Change, and Forestry. The goal is to improve the consistency and completeness of greenhouse gas emissions and removals reporting. The refinement offers updates to the guidance, including improved emission factors, new methodologies, and examples to aid compilers in better estimating emissions and removals in the AFOLU sector (IPCC, 2006).

Mapping soil organic carbon (SOC) and soil inorganic carbon (SIC) densities and estimating their pool sizes are crucial for understanding sequestration potential and losses from a global warming perspective (Sreenivas et al., 2016). There remains significant uncertainty regarding global forest cover due to the lack of comprehensive long-term studies on forest cover change (Reddy et al., 2015). A major uncertainty exists in soil organic carbon dynamics, necessitating future studies to consider both tree dynamics outside forests and soil for a complete understanding of terrestrial carbon dynamics (Kaul et al., 2011).

The largest carbon fluxes result from the conversion of forest land to cropland and wastelands, highlighting the need for more reliable district-based data to improve estimates of net carbon flux from land use changes (Kaul et al., 2009). Soil organic carbon plays a critical role in the global carbon cycle as the largest terrestrial carbon pool. Soil can either sequester or emit greenhouse gases depending on land use and management. Most global climate change models predict a loss of carbon from soils due to global warming; however, restoring eroded and degraded soils and intensifying agriculture can lead to carbon sequestration. Estimated soil organic carbon densities by forest type can be used in models to estimate net carbon release from deforestation and historical losses in the SOC pool in Indian forests (Chhabra et al., 2003).

A study by Rahman et al. (2021) analysed the land use land cover (LULC) dynamics of Dhaka city and evaluated the impact of LULC changes on ecosystem services value (ESV).

The study showed a 59.55% decrease in ESV, from 142.72 million USD in 1990 to 57.72 million USD in 2020, due to the development of built-up areas replacing agricultural land, waterbodies, and forests. Water supply, waste treatment, and disturbance regulation were identified as major contributors to ESV in Dhaka.

The history and growth of hydroelectric projects in North-East India are critical to India's vision of becoming a developed nation by 2020, with the region playing a vital role due to its substantial water resources from the Brahmaputra-Barak and Irrawaddy River systems. Despite having a hydro potential of 63,257 MW, only 1,911 MW has been harnessed so far, representing just 3.02% of its potential. Fully utilizing this hydro potential could position North-East India as "The Power House of India" (Das et al., 2013).

Reddy et al. (2016) reported that while deforestation in India has declined over eight decades due to national policies aimed at conservation and sustainable management, the increase in plantations has outpaced the loss of natural forests. However, ongoing forest cover loss could have significant conservation implications for endemic species in the Andaman region.

The replacement of natural vegetation with plantation crops, such as rubber in Kerala, has negative environmental implications. Rubber plantations, which now cover about 21% of Kerala's cropped area, often replace natural vegetation. Despite their economic benefits, these plantations pose environmental challenges. Site-specific studies and intercropping alternatives are recommended to mitigate adverse impacts. Government agencies promoting rubber plantations should consider these environmental issues in future decision-making (Chattopadhyay, 2021).

Pasha et al. (2023) analysed the spatiotemporal dynamics of rubber expansion in Tripura using multi-year and multi-sensor data, providing a framework for long-term land cover analysis. The findings have important implications for regional land management and policy making, balancing economic development with environmental sustainability.

CHAPTER-3

MATERIALS AND METHODS

3.1 Study area

To understand the spatiotemporal changes in the vegetation and carbon dynamics we have selected two sites.

1. Kottayam district, where there is a predominance of conversion of natural landscape to plantations.
2. Pualreng Wildlife Sanctuary in the Kolasib district is impacted by anthropogenic disturbances that are mainly due to infrastructure development.

Study Site-1 Kottayam District of Kerala

Kottayam is a city in the central part of the Indian state of Kerala and serves as the administrative capital of Kottayam district. It is uniquely positioned between the towering Western Ghats to the east and the Vembanad Lake and the paddy fields of Kuttanad to the west. The district covers an area of 2,208 km² and is naturally divided into highland, midland, and lowland regions, with the midland regions being the most extensive. Meenachil and Kanjirappally Taluks feature highland and midland areas, while Kottayam, Changanassery, and Vaikom Taluks include midland and lowland areas. The soil composition varies, with Laterite soil in Kanjirappally and Meenachil Taluks, and Alluvial soil in Vaikom, parts of Changanassery, and Kottayam Taluks. Notably, the district lacks a coastal area.

Kottayam experiences a tropical climate with hot seasons in the plains and significant rainfall throughout the year. The hot season spans from March to May, followed by the southwest monsoon from June to September. October and November mark the post-monsoon or retreating monsoon season, with temperatures rising and heat nearly as intense as in summer. The northeast monsoon occurs from December to February, with rain usually ceasing early in January. The district typically receives an annual average rainfall of 3,130.33 mm (<https://kottayam.nic.in/>).

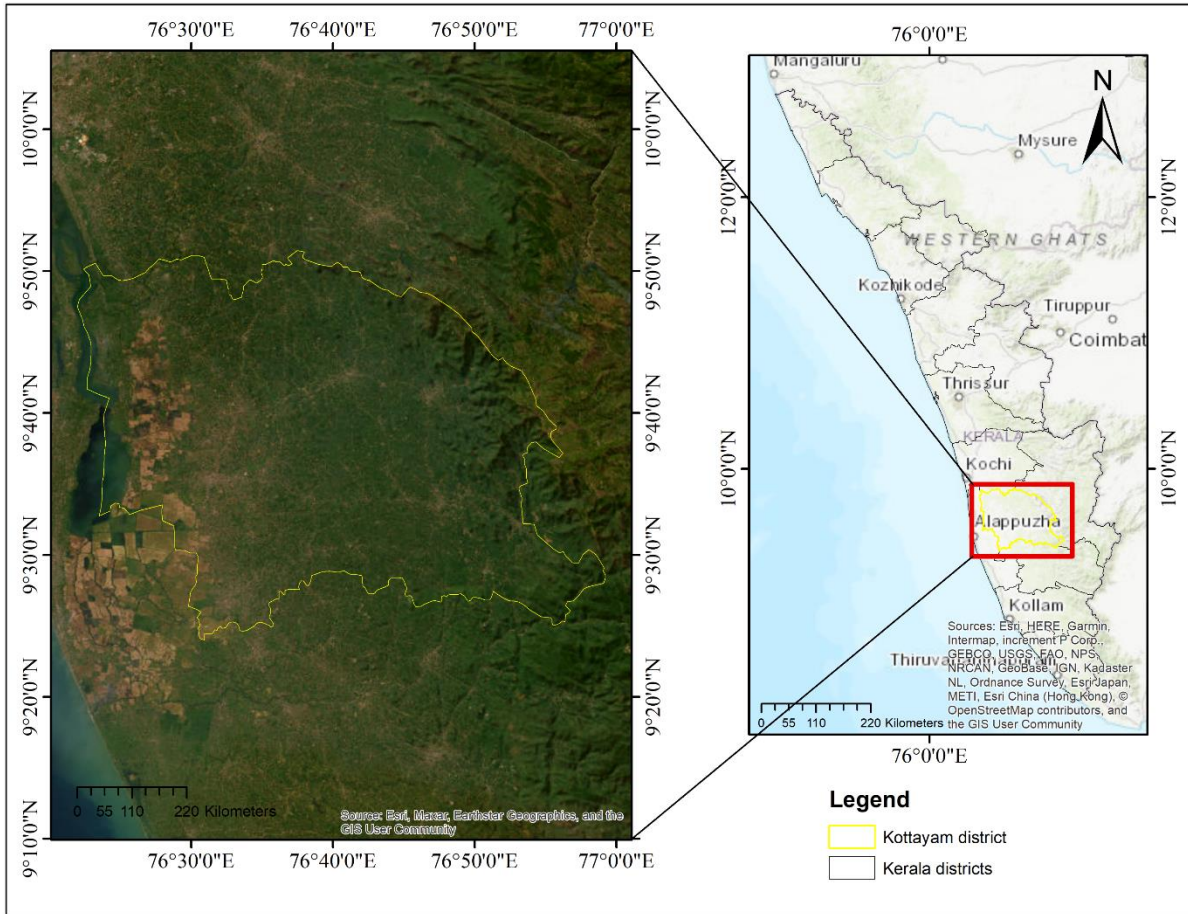


Figure 3: Study area map of Kottayam district of Kerala

Table 2: Demography of Kottayam District (Source: <https://kottayam.nic.in/>)

Demography	Estimate
Area	2208 Km ²
Population	19,74,551
No. of Revenue Divisions	2
No. of Block Panchayats	11
No. of Taluks	5
No. of Municipalities	6
No. of Villages	100
No. of Gram Panchayats	71
Literacy Rate	97.21%
No. of Constituencies	9

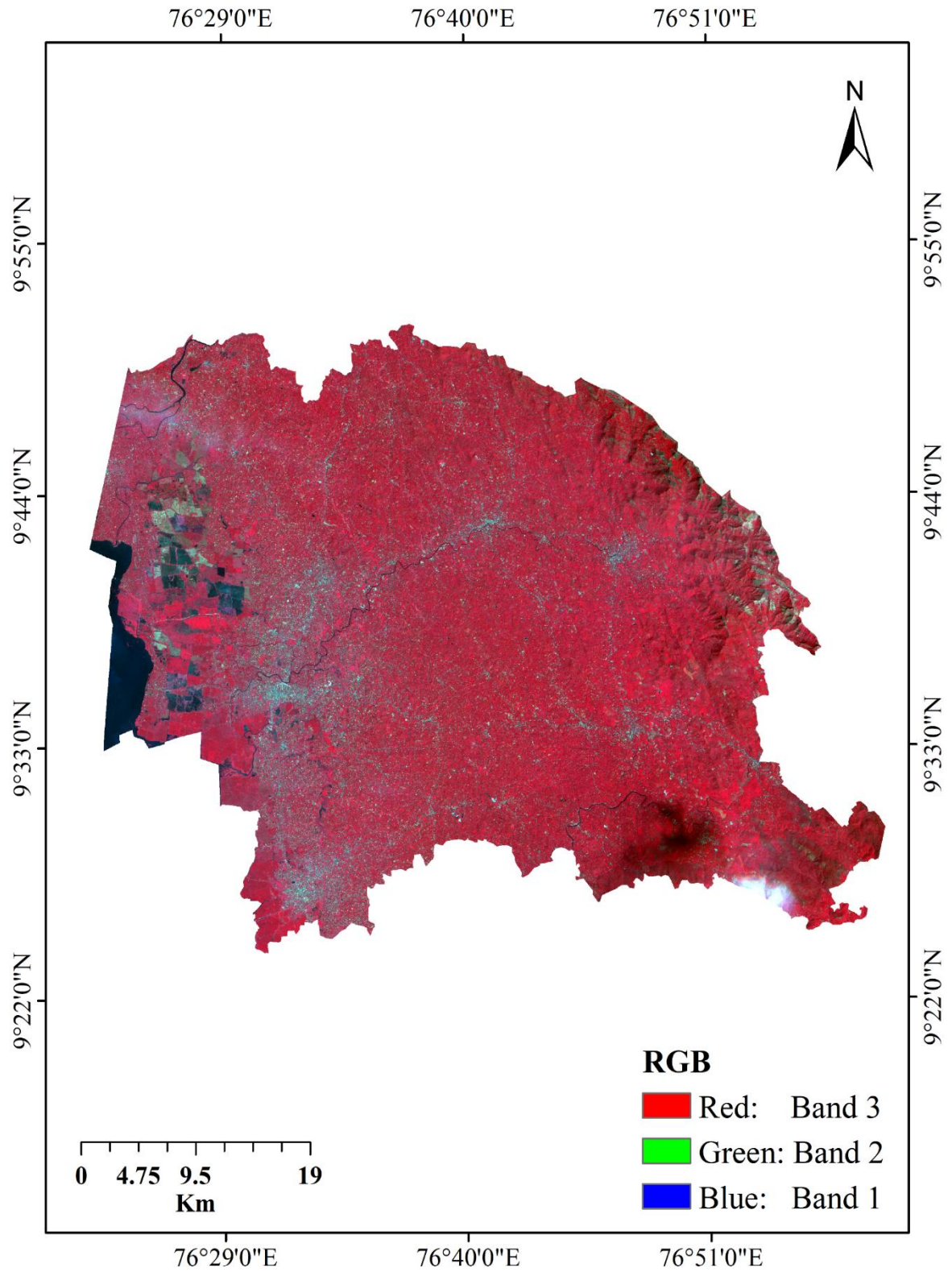


Figure 4: False Colour Composite (FCC) of the study area

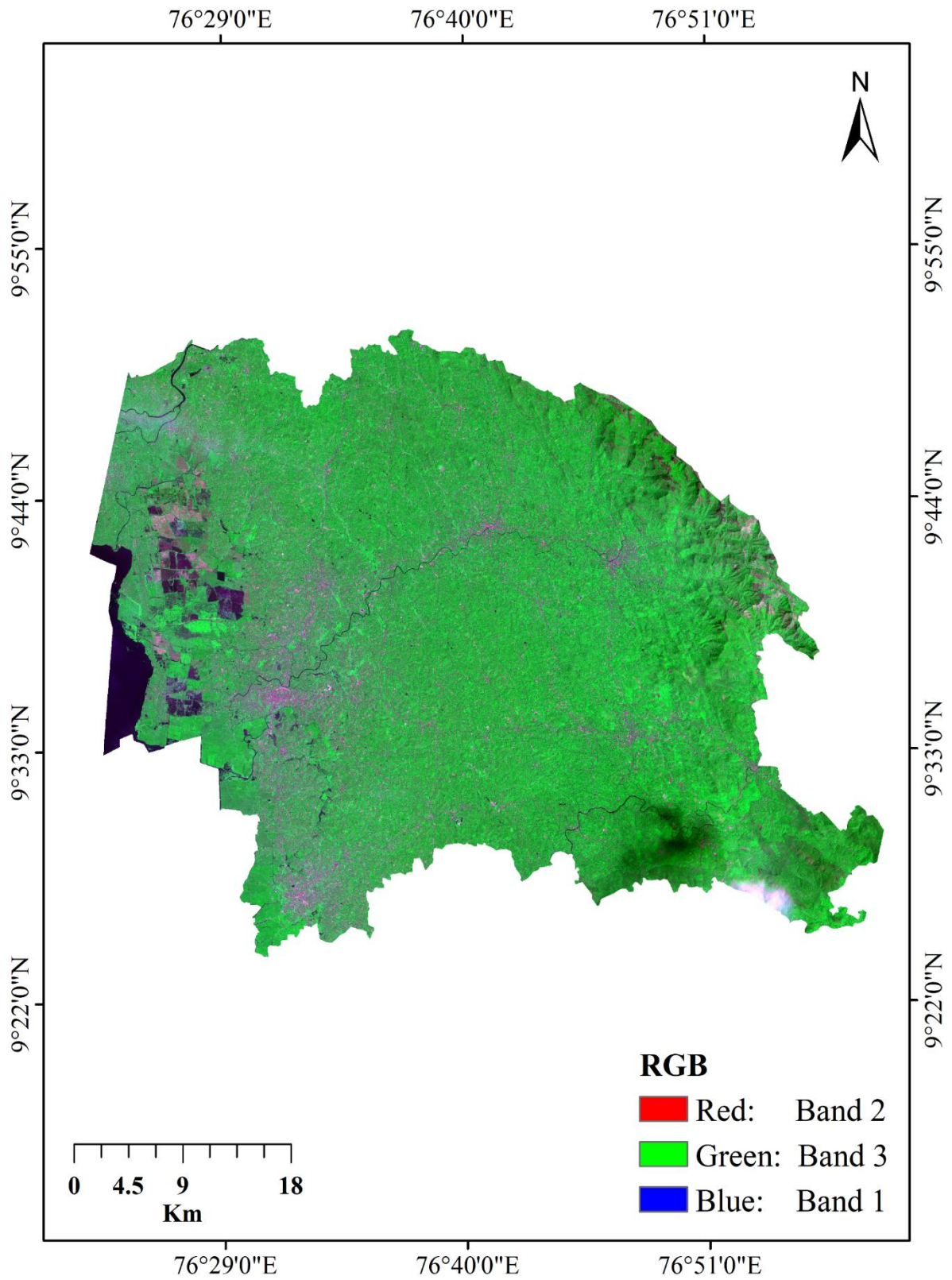


Figure 5: Natural Colour Composite (NCC) of the study area

Literature review has been done using publish or perish (<https://harzing.com/>), dimension web, (<https://www.dimensions.ai/>), and bibliometric analysis was carried out using VOS viewer (<https://www.vosviewer.com/>).

3.2 Publish or perish

Publish or Perish (PoP) is a free Windows software designed to assist academic scholars in retrieving and analysing citations. This comprehensive, feature-rich tool utilizes various data sources, such as Microsoft Academic Search (MSA) and Google Scholar (GS), to collect raw data. It then processes and presents this data through different metrics, including Hirsch's h-index, contemporary h-index, Egghe's g-index, and age-weighted citation rate. Publish or Perish provides an array of citation metrics, such as the number of papers, total citations, and the h-index. Results are displayed on-screen and can be copied to the Windows or macOS clipboard for use in other applications or saved in various output formats for future reference or further analysis. The software includes a detailed help file with search tips and additional information about the citation metrics (<https://harzing.com/>).

3.3 Open Alex API

Open Alex is a fully open catalogue of the global research system, named after the ancient Library of Alexandria and created by the non-profit organization OurResearch. This technical documentation covers the Open Alex API and data snapshots, guiding you on how to set up your code to access Open Alex's data. If you prefer to explore the data manually, you might be more interested in OpenAlex Web. The OpenAlex dataset encompasses various scholarly entities and their connections, including works, authors, sources, institutions, topics, publishers, and funders. Together, these form an extensive web (technically, a heterogeneous directed graph) with hundreds of millions of entities and billions of connections. OpenAlex serves as an open alternative to industry-standard scientific knowledge bases like Elsevier's Scopus and Clarivate's Web of Science, offering significant advantages in inclusivity, affordability, and availability compared to these paywalled services (<https://docs.openalex.org/>).

3.4 VOS Viewer

VOS viewer is a software tool designed for constructing and visualizing bibliometric networks, such as those involving journals, researchers, or individual publications. These networks can be based on citation, bibliographic coupling, co-citation, or co-authorship

relations. Additionally, VOS viewer offers text mining capabilities to build and visualize co-occurrence networks of key terms from scientific literature. The tool allows detailed exploration of these visualizations with zoom and scroll functions similar to Google Maps, and employs a smart labelling algorithm to prevent label overlap. Density visualizations provide quick overviews of key areas in a bibliometric network, while overlay visualizations can depict developments over time. Advanced techniques for network layout and clustering are included, with adjustable parameters for fine-tuning results. Natural language processing techniques are available for creating term co-occurrence networks from English-language texts, and the software can algorithmically distinguish between relevant and non-relevant terms. VOS viewer also supports creating various bibliometric networks (e.g., co-authorship, bibliographic coupling, co-citation) and can reduce the influence of publications with many authors, citations, or references through fractional counting. Data cleaning can be performed using thesaurus files (<https://www.vosviewer.com/>).

3.5 Bibliometric Analysis

Bibliometric analysis is carried out to understand the research trend related to the study area and we can map and assess the impacts of the related publications. The publications from the dimension web, (<https://www.dimensions.ai/>) were used for the mapping which facilitates the analysis. The dimension web provided related publications in terms of key words and we can sort the data according to our preferences. For further analysis, a VOS viewer is used which helps in performing the analysis. Country-wise analysis is carried out to understand the network of related publications in the world. The bibliometric analysis provided a comprehensive overview on the number of publications in each country in their network on rubber and remote sensing studies. The below figure shows the network analysis of publications country-wise related to natural rubber and remote sensing studies in the world. This can be done to be visualised through the network of related publications of this study.

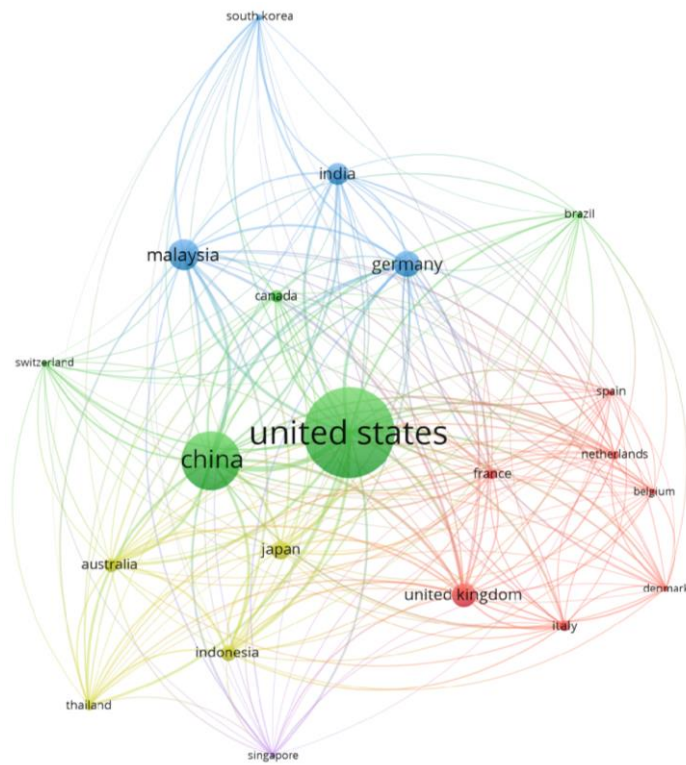


Figure 6: Network map of publications related to this study

3.6 Materials

This study aimed to monitor the expansion of natural rubber (NR) in the Kottayam district of Kerala from the year 1970s to 2023. Satellite data from the LISS 4 and Landsat were used to study the expansion of NR for two time periods. Images from Landsat 7 ETM+ were used for the study of the year 2001 and images from LISS 4 were used for the study of the year 2023. The Landsat 7 data with 15 m resolution was accessed from the US Geological Survey (USGS) (<https://earthexplorer.usgs.gov/>) on 3rd March 2001. The LISS 4 data with 5.8 m resolution was accessed from the Bhoonidhi portal (<https://bhoonidhi.nrsc.gov.in/>) on 8th February 2023. For a better understanding of the spatial-temporal dynamics of NR, satellite data with less cloud coverage were used. Images from the months of defoliation of rubber, from February to April were used for obtaining high spectral reflectance. These are the months when the leaves of natural rubber appear to be in peak green. Along with the satellite data, topographic maps of the Kottayam district for the years 1970 and 2005 with a scale of 1:50,000 were obtained from the Survey of India (SoI) (<https://www.surveyofindia.gov.in/>). The FSI reports were analysed to compare the forest cover with the area under rubber plantations in the Kottayam district. The Above Ground Biomass (AGB) data of Santoro is also accessed from (<https://climate.esa.int/en/>) for the year 2018 to estimate Above Ground Carbon (AGC). The

Digital Elevation Model (DEM) for the Kottayam district, with a 30-meter resolution, was obtained from the Shuttle Radar Topography Mission (SRTM) (<https://portal.opentopography.org/>) to gain a clearer view of the area's topography. Additionally, rainfall data for Kottayam district was reviewed from the India-Water Resource Information System (WRIS) (<https://indiawris.gov.in/>) on April 15, 2024.

3.7 Comprehensive Rubber Information System Portal (CRISP)

The Rubber Board and Digital University of Kerala have developed a Comprehensive Rubber Information System Platform (CRISP) for the rubber growers of Kerala. For the comparison of mapped rubber plantations, the rubber area statistics of the Kottayam district during the year 2019-2020 are used. The age of the rubber plantations falls under this area; statistics were 3 years and above. Satellite data acquired for the year 2019 for March or April. Sentinel 2A/2B data with 10m resolution is used for the mapping of rubber plantations in the district. According to CRISP, the total area under natural rubber in Kottayam district is 1,07708 Ha. The percent of NR area according to the geographical area of the district is 48.90 %.

3.8 Field survey data

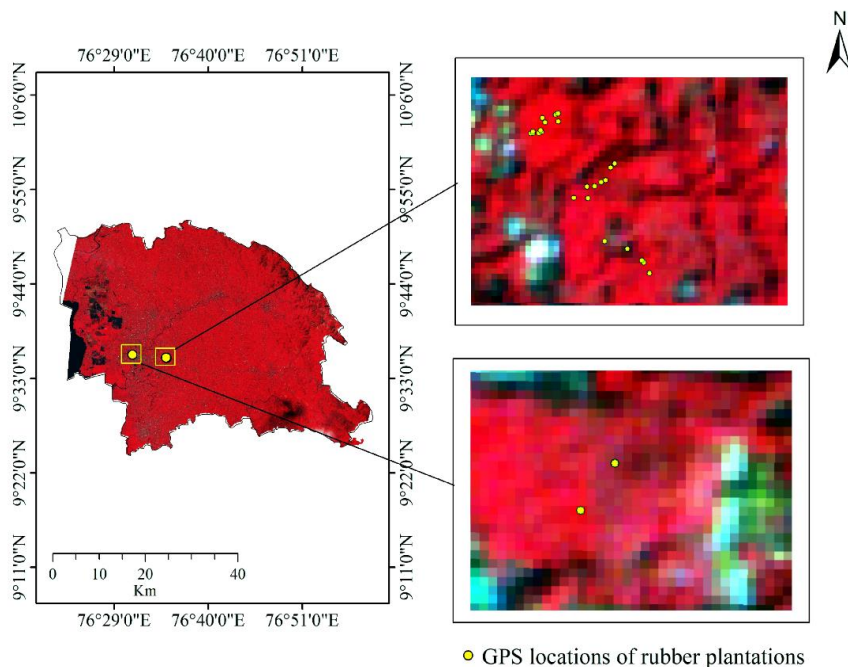


Figure 7: GPS locations of rubber plantations collected from the study area

3.9 Digital Elevation Model (DEM)

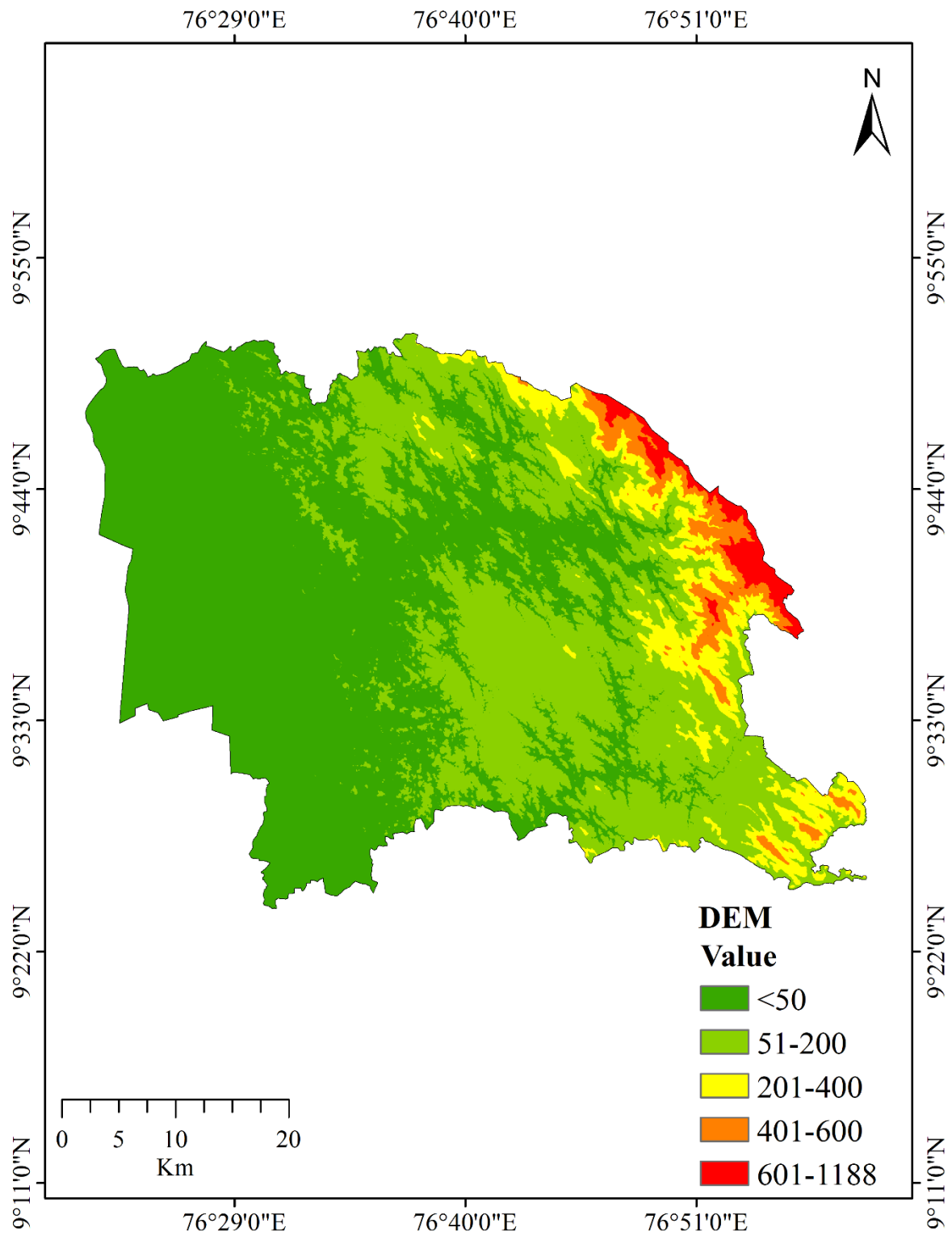


Figure 8: Map showing the various classes of digital elevation map of the study area

3.10 Methods

Geo rectification is done for the toposheets using ArcGIS and QGIS software. The GIS layers for the vegetation classes were created from the toposheets. From this digitized polygon area, natural rubber plantations were calculated for the years 1970 and 2005. Rubber plantations show high spectral reflectance compared to the co-occurring vegetation types or land cover. This is critical for the mapping of natural rubber. The multi-spectral bands of the satellite data obtained from the LISS 4 and Landsat 7 were merged to obtain an image enhancing the specific features in the land. Two time periods of unsupervised classification are done for mapping rubber plantations for the years 2001 and 2023 using Erdas Imagine software. Area under different land cover or vegetation types were calculated from the classified image. From this, areas under rubber plantations were extracted. The obtained area under rubber plantation is compared with the forest cover reported in the Forest Survey of India (FSI) reports and also with the rubber area statistics reported in the Comprehensive Rubber Information System Platform (CRISP) of the Kottayam district. Above Ground Biomass (AGB) and Above Ground Carbon (AGC) in the study area are also estimated for the year 2018. From the AGB data AGC is calculated for each density class. Normalized Difference Vegetation Index (NDVI) is also performed for the year 2001 and 2023 of the study area to understand the health of the vegetation or to detect the green cover. For understanding the pattern of annual rainfall in the Kottayam district the rainfall trend is prepared for the year 1901-2021.

Android-based field survey is also conducted in some parts of the study area using the GeoTag and epicollect5 applications. Classified forest and rubber plantations and identified different age groups of rubber plantations in the field site which are directly linked to the Above Ground Biomass (AGB). From each site, the GPS points were collected for the rubber plantations. The age-wise rubber plantations and their latitude and longitude and the average girth for each age group were measured. Geo-located photographs of the rubber plantations were also captured from the field site. For a better understanding of the rainfall pattern in the Kottayam district, the average annual rainfall trend is prepared for the years 1901-2021.

Study Site- 2 Pualreng Wildlife Sanctuary in Mizoram

Pualreng Wildlife Sanctuary (PWS) is situated in the Kolasib District in the state of Mizoram, India which was established in 2004. The sanctuary is known for its extensive biodiversity of endemic flora and fauna. It belongs to the North-eastern biogeographic zone of India. It was established on 29th July 2004. This date marks the formal recognition of the

sanctuary as a protected area for the conservation of its biodiversity and natural habitat. It covers an area of approximately 50 km². This protected area spans this region and is dedicated to the conservation of the diverse flora and fauna found within its boundaries (Rawat et al., 2017).

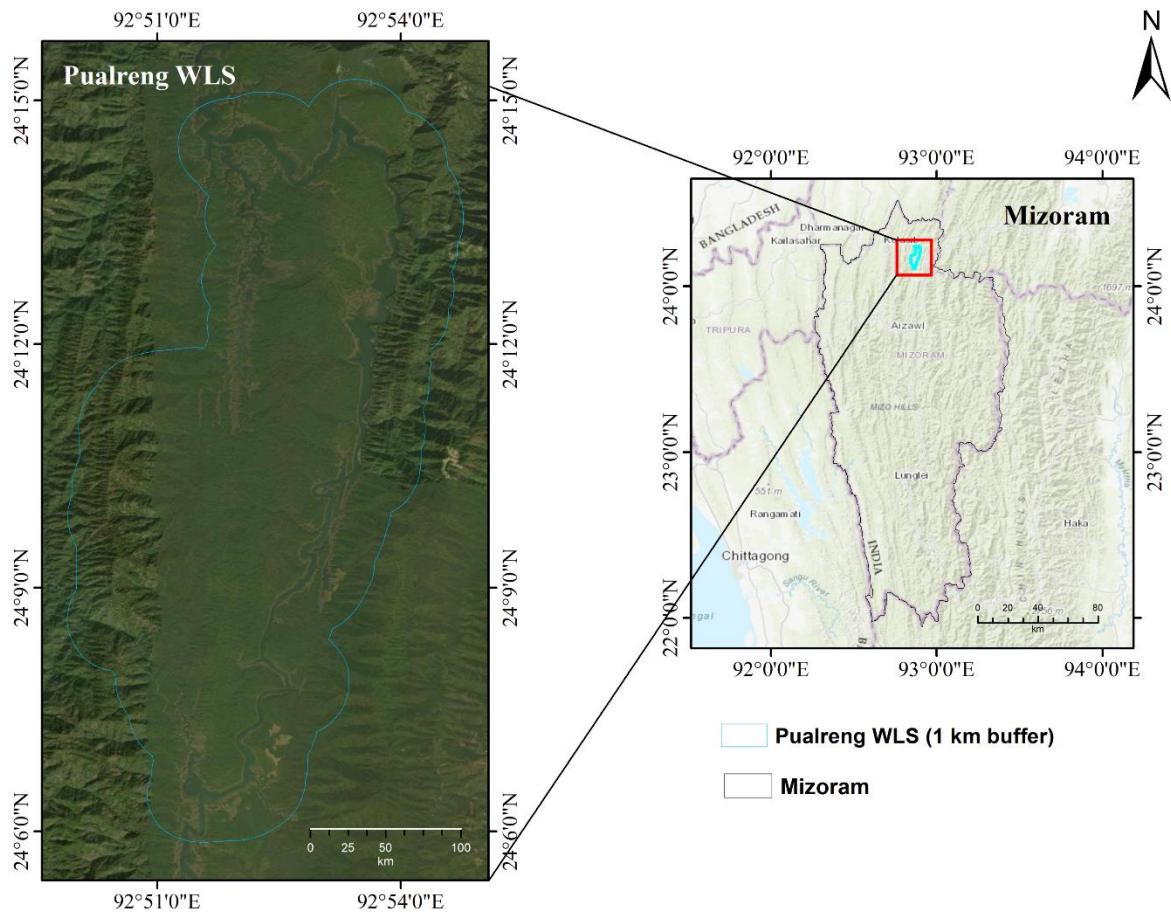


Figure 9: Study area map of Pualreng Wildlife Sanctuary

This sanctuary is situated between 24° 6'35" - 24° 14'16'21" North Latitude and 92°50'17.6" - 92° 54 '2.64' ' East longitude. Pualreng Wildlife Sanctuary is dedicated to conserving and protecting 16 endemic species of plants and animals, including *Ficus religiosa*, *Mesua ferrea*, *Michelia champaca*, *Acrocarpus fraxinifolius*, *Bombax ceiba*, Clouded leopard, Hoolock gibbon, Sun bear, Slow loris, Phayre's leaf monkey, Sambar, Serow, Khaleej pheasant, Peacock pheasant, Common hill partridge, and Pied hornbill. Notably, Doria's foam-nesting tree frog was rediscovered here after 108 years, with its last known sighting in Tenga Valley, Arunachal Pradesh, in 1912 (Muansanga et al., 2011). The sanctuary features a semi-evergreen tropical forest with sandy soil and sedimentary rocks. Its elevation ranges from 260 m to 750 m, and nearby villages include North Hlimen, Thingthelh, Bukpui, Ratu, and North

Khawdungsei. The climate is mild and pleasant, with summer temperatures between 20°C and 30°C, and winter temperatures between 10°C and 20°C, receiving an annual rainfall of 2000 mm to 3900 mm. The primary economic activity in surrounding villages is agriculture, particularly jhum cultivation (slash-and-burn). However, expanding agricultural land due to population growth has led to degradation and disturbance in both buffer and core zones of the sanctuary (Vanlalnunpuia et al., 2022).

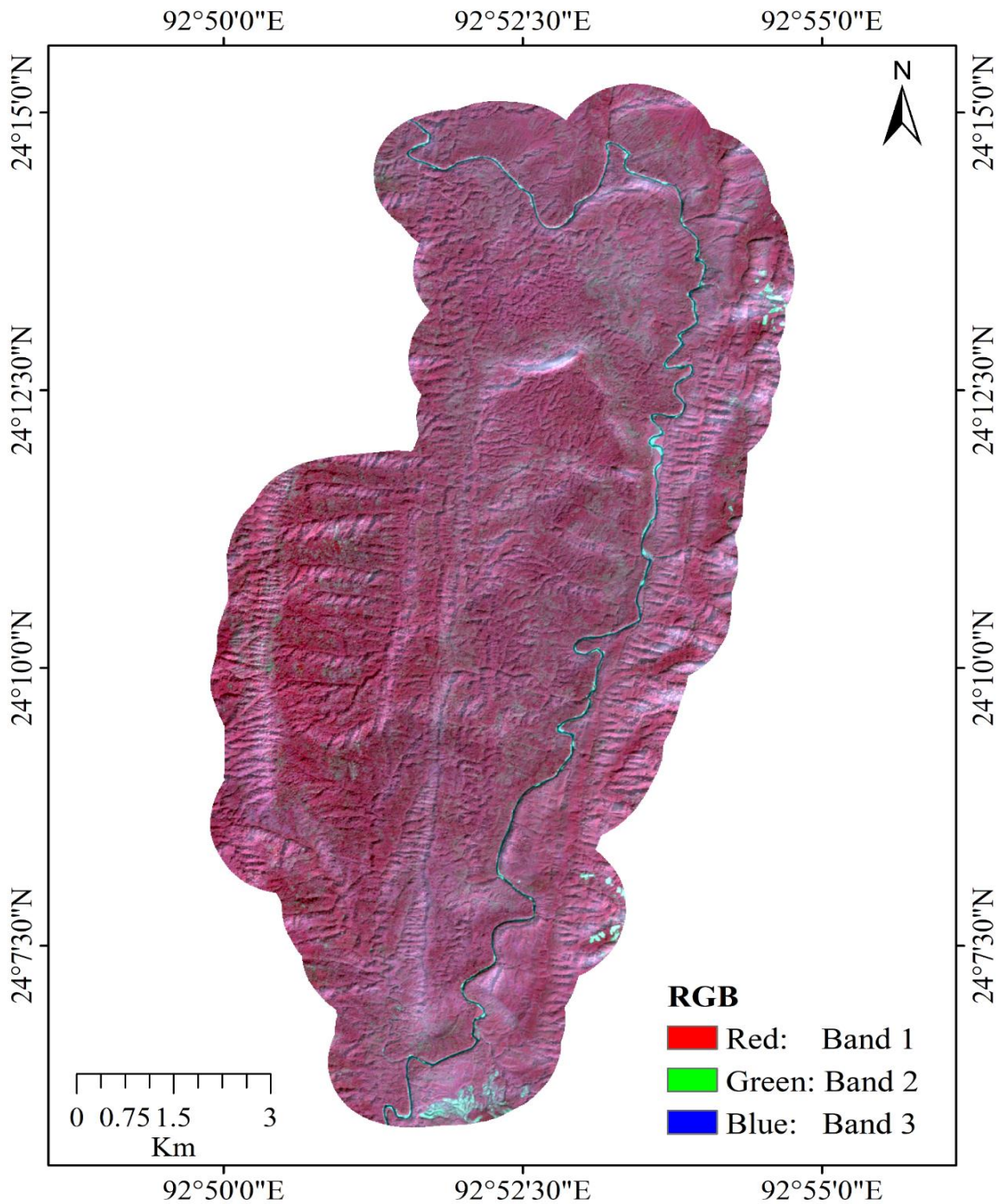


Figure 10: FCC of the study area for the year 2016 with a buffer of 1 Km

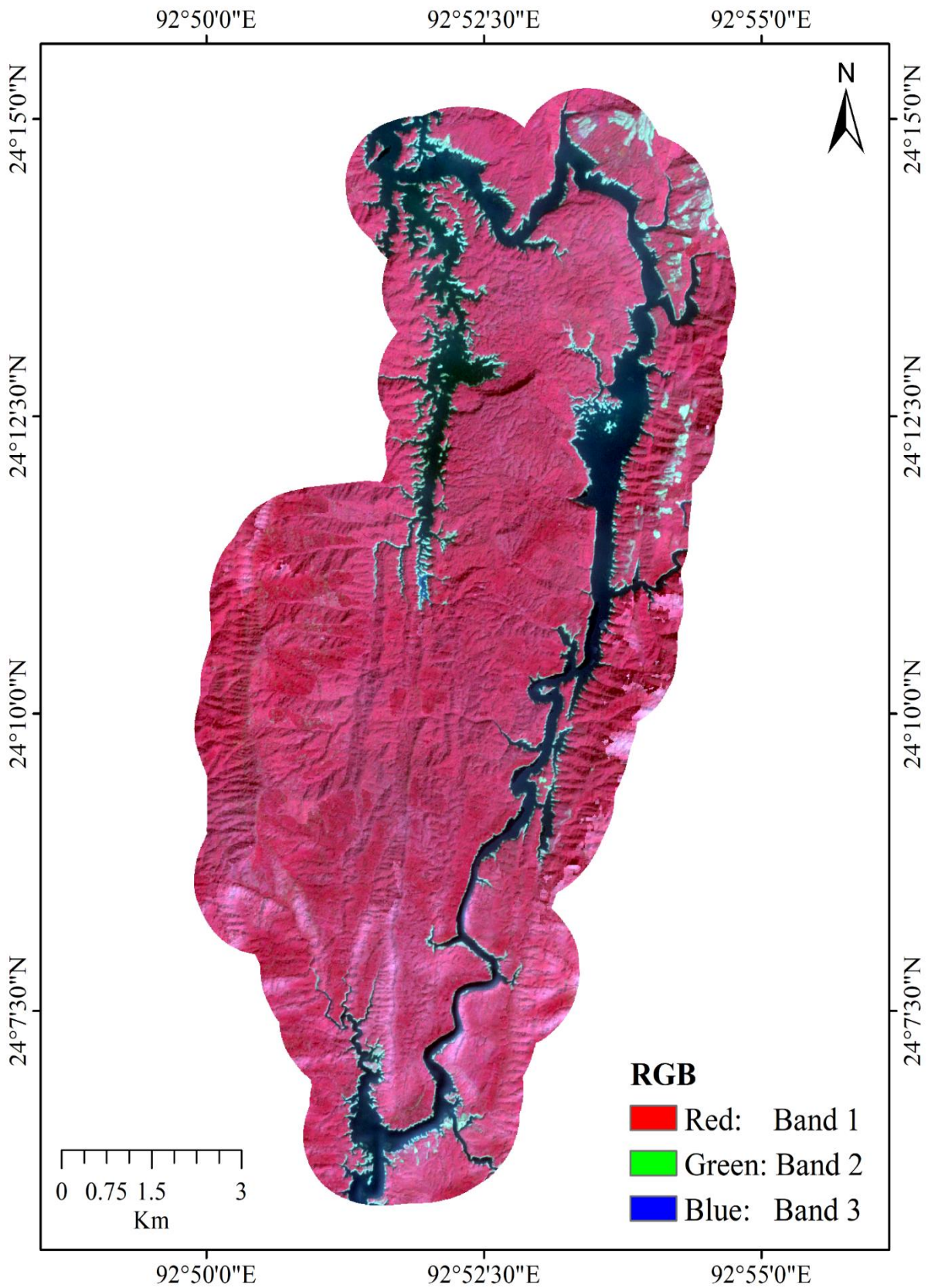


Figure 11: FCC of the study area for the year 2022 with a buffer of 1 Km

3.11 Materials

This study was carried out to estimate the tree loss in the Pualreng Wildlife Sanctuary in the past two decades. Spatial data is essential for monitoring the tree loss that happened in the wildlife sanctuary during the past two decades. The spatial data for the years from 2001 to 2022 were collected. Satellite data from the sentinel 2A satellite is used to understand the present scenario of the PWS. This data is downloaded for February with a 10m resolution from the (<https://scihub.copernicus.eu/>). The satellite data from the Landsat series were downloaded to monitor the tree loss in the past two decades. The images from Landsat 7 were accessed for the monitoring of tree loss in the study area by the US Geological Survey (USGS) (<https://earthexplorer.usgs.gov/>) for the year 2003 with a 30m resolution. Images from Landsat 8 were accessed for the year 2014. The satellite data with less cloud coverage were used for a better understanding of the loss that happened in the study area. The Digital Elevation Model (DEM) with a 30-meter resolution for the study area was obtained from the Shuttle Radar Topography Mission (SRTM) (<https://portal.opentopography.org/>) to gain a clearer understanding of the area's topography. Additionally, rainfall data for the Kolasib district was accessed from the India-Water Resource Information System (WRIS) (<https://indiawris.gov.in/>) portal.

Methods

The spatiotemporal analysis is critical to estimating the Land Use Land Cover (LULC) changes due to developmental activities like the Tuirial hydroelectric project that came into existence in the Kolasib district in Mizoram in 2014. This study estimated the area under forest loss for two decades from 2001 to 2022. A GIS layer is also created for this data showing the forest loss that happened each year in the protected area due to the submergence of land caused by the rise in the water level. The cumulative tree loss for these years is also calculated and analysed the total loss occurred in the study area due to this development. Normalized Difference Vegetation Index (NDVI) is performed for the year 2016 and 2022 of the study area for the better understanding of the health of the vegetation or to detect the green cover in the protected area. For understanding the pattern of annual rainfall and the impact of rainfall variability in the Kolasib district the rainfall trend is prepared for the year 1901-2021.

3.12 Digital Elevation Model (DEM)

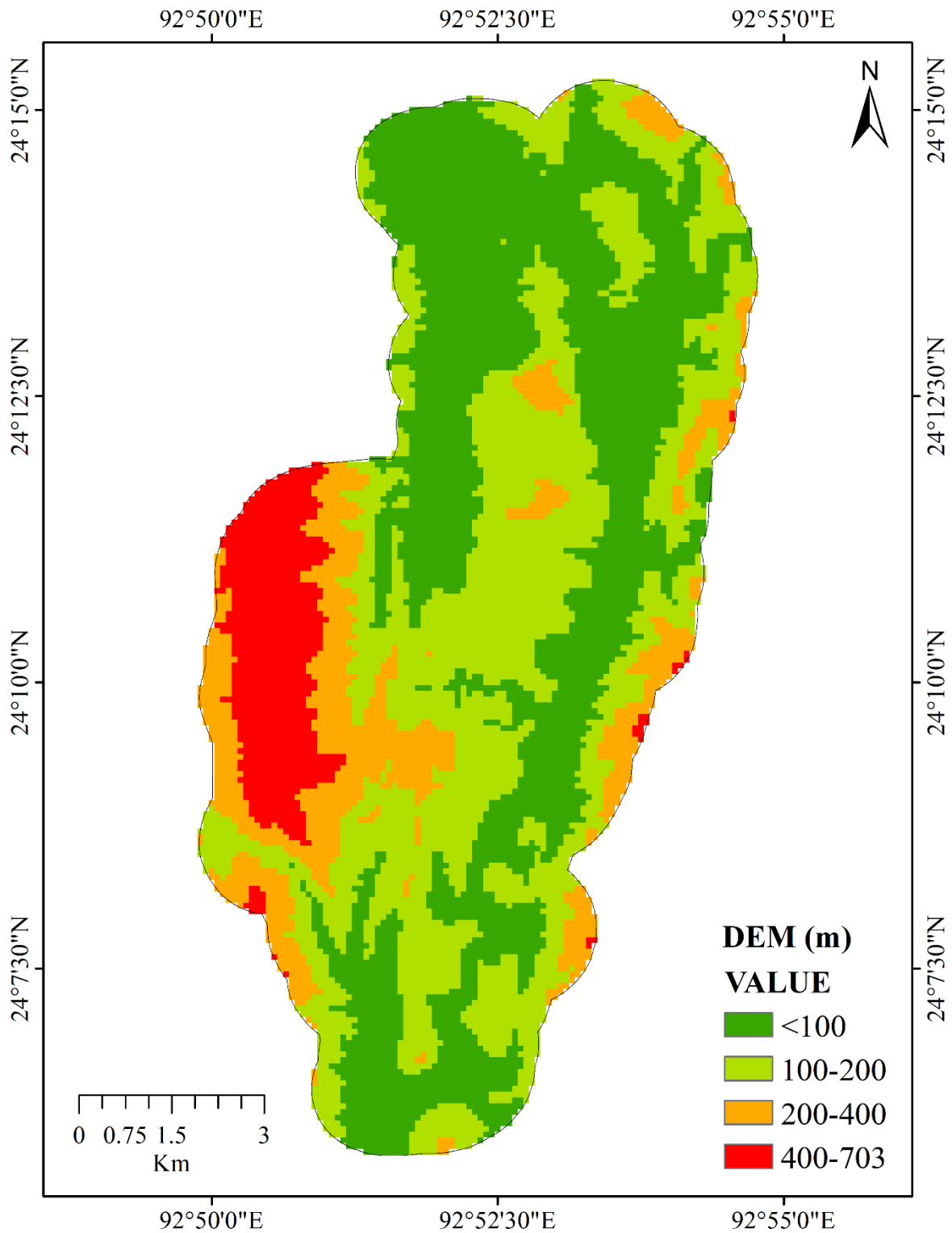


Figure 12: Map showing the various classes of digital elevation map of the study area

CHAPTER-4

RESULTS AND DISCUSSION

Study site - 1

In this study we have evaluated the forest cover dynamics using FSI and multitemporal data to better comprehend the various forest and plantation types. According to the Forest Survey of India (FSI, 2021), forest cover is defined as any land larger than 1 hectare with a tree canopy density exceeding 10 percent. The forest cover reported in the Indian State of Forest Report (ISFR) does not differentiate between natural or manmade tree crops or species. It includes all types of lands, regardless of ownership, land use, or legal status. Therefore, any area that meets these criteria, including various tree species, bamboo, fruit-bearing trees, coconut palms, and lands classified as forest, private, community, government, or institutional, is considered part of the forest cover.

In this study we used natural forest definition because of the wide variability in the carbon sequestration. The results obtained were compared with the FSI statistics. It is clearly indicating that 49.82% of the geographical area falls under forest during the year 2021. However, it is noticed that 56.93% of the total geographical area is falling under rubber plantations. It is also found that 4.48% of the geographical area is under natural forest including teak monoculture. Out of this, 2.01% falls under teak plantations. The results indicate that the area under rubber plantations in the district has increased from 5.25% in 1970 to 56.93% in 2023 in the Kottayam district.

4.1 Forest cover in Kottayam district

According to the FSI reports from 2003 to 2021, we can see an increase in the forest cover in the Kottayam. The geographical area of the Kottayam district was 2203 Km² which was increased to 2206 Km² in 2023. Throughout these years the total forest cover of the district increased from 29,500 ha in 2003 to 1,09,900 ha in 2021. Out of 2206 Km², 49.82 % of the geographical area falls under natural forest. It was found that there is an increase of 36.43 % of natural forest out of the geographical area in the district between the years 2003-2021. In 2021, the area under Very Dense Forest (VDF) was reported to be 11.31 Km² and Moderately Dense Forest (MDF) constituted 525.73 Km² and Open Forest (OF) constituted 562.01 Km². The below table shows the increase in the forest cover in Kottayam district of Kerala from 2003-2021 according to the area under forest cover reported in forest survey of India (FSI).

Table 3: Forest cover in Kottayam district reported in FSI

SL. No	Geographical Area (GA) (in sq.km)	VDF	MDF	OF	Total (in sq.km)	Percent of GA	Year
1	2203	0	185	110	295	13.39	2003
2		1	187	106	294	13.35	2005
3		13	546	336	895	40.63	2009
4		12	542	335	889	40.35	2011
5		12	534	344	890	40.4	2013
6		12	530	341	883	40.08	2015
7	2206	12	521	434	967	43.83	2017
8		12	531.95	560.34	1104.29	50.06	2019
9		11.31	525.73	562.01	1099.05	49.82	2021

4.2 Mapping of natural rubber plantations in the study area

We have mapped the rubber plantations for the years 1970, 2001, 2005 and 2023 to analyse the expansion or dynamics of rubber plantations in the Kottayam district. The spatiotemporal analysis is necessary for estimating the spread of rubber plantations in the study area. we can see that there is a remarkable increase in the rubber plantations from 1970 to the present year in the study area. The GIS layer created for the year 1970 from the toposheet indicates that the total area falling under rubber plantation is 11597 Ha which was gradually increased to 125591 Ha in 2023. In 2001 the area obtained was 21147.8 Ha and 23319.5 Ha for the year 2005. For the same year the area of forest cover reported in the FSI report for the Kottayam district was 29400 Ha.

It is noticed that most of the land conversions happened from the agricultural land, other vegetation types and some portions of natural forest. During the 2005 to 2023 a substantial increase in the rubber plantation can be seen.

The below graph shows the increase in the forest cover in Kottayam district from 2003 to 2023 and the area under rubber plantations mapped for the year 1970, 2001, 2005, and 2023

for the present study. The axes represent the area of forest cover and rubber plantations for each year in Km².

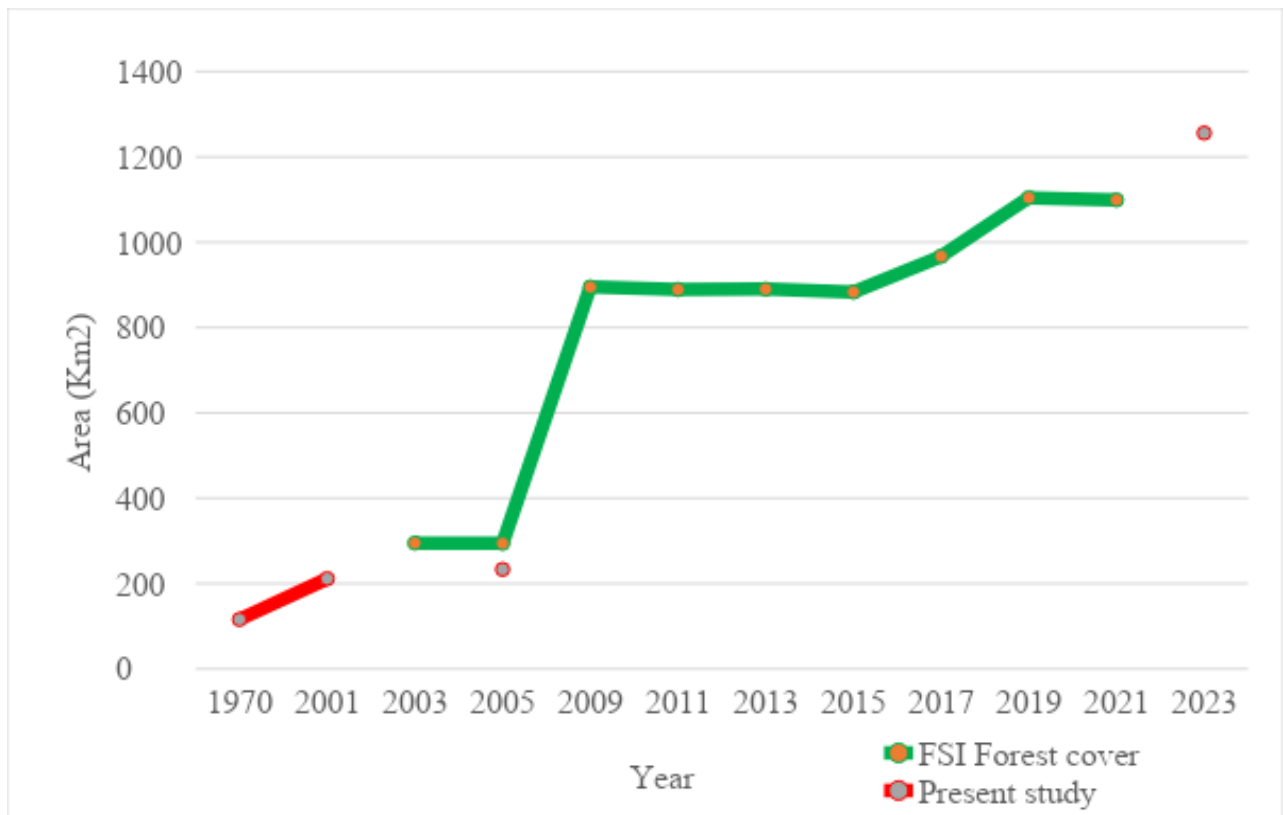


Figure 13: Graph showing increase in the area under forest cover and rubber plantations

Table 4: Total area of rubber for respective years

Year	Total Area of Rubber (Ha)
1970	11597.77
2001	21147.8
2005	23319.5
2019 (CRISP)	109900
2021 (FSI)	107708
2023	125591

4.3 Mapping LULC Dynamics in the Kottayam district - Results of digital analysis

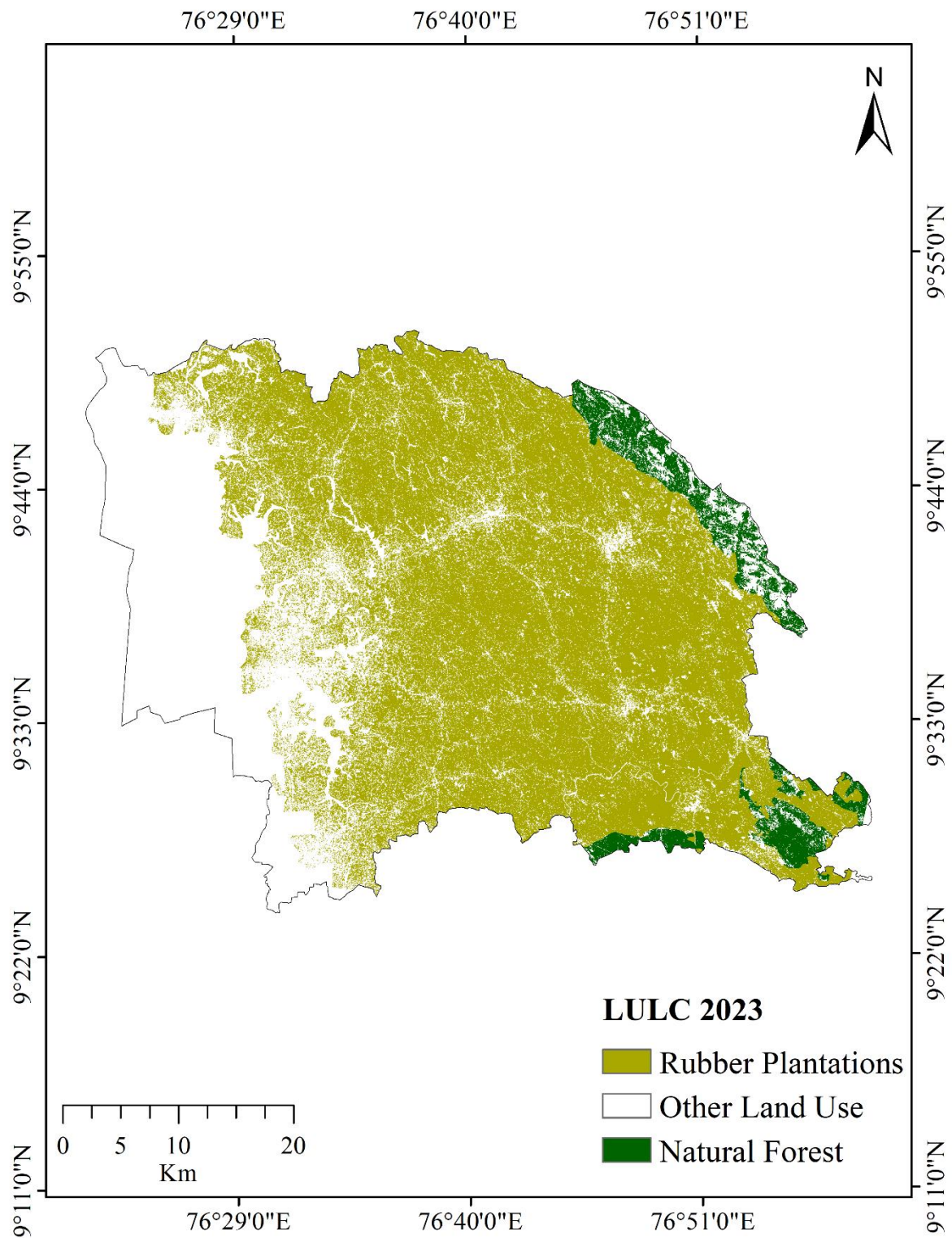


Figure 14: Map representing LULC in the year 2023

The mapping of rubber plantations in Kottayam district will give a comprehensive view into the spatial distribution, extent, and density of rubber cultivation in the region. Satellite images capture the forest cover with varying spectral reflectance which will help in the classification of forest cover in the region. Unsupervised classification helps to obtain images with different land cover classes. Based on the high spectral reflectance properties of rubber plantations we could separate the natural rubber from other classes. The mapping of rubber plantations in Kottayam district utilizing satellite data is based on their spectral signatures and spatial characteristics. The extent of the rubber plantations can be clearly understood from the map. Through this type of classification, it enables an accurate depiction of rubber plantations that exist in the district for each year.

The map depicts the spatial distribution and extent of rubber monoculture within the Kottayam district and it also highlights the areas having high concentration of rubber. From the LULC classification for the year 2023, it is noticed that the high density is concentrated on the eastern portion of the Kottayam district where there is natural forest including teak plantations and rubber monoculture exists and low density is found to be in the western portion. The area under natural forest including teak monoculture is found to be 9611 Ha and area under rubber plantation is 125591 Ha and the remaining other land use consists of 81362.7 Ha of area. The unsupervised classification is done using LISS IV satellite data. The LISS-IV Camera, launched by ISRO aboard the Resourcesat-1 satellite in 2003, is a high-resolution multispectral instrument. It features three spectral bands, a resolution of 5.8 meters, and a swath width of 23 kilometres from an altitude of 817 kilometres (Paul et al., 2006). This image aided in capturing the rubber plantations with more accuracy than the other satellites. This image with high spatial resolution can identify finer details on the ground which helps in the mapping of smaller patches of rubber.

As our primary focus was on rubber plantations, we have mapped rubber plantations in the district for the year 2001 using Landsat 7 image with 15 m resolution. Landsat 7 was launched on April 15, 1999, from Vandenberg Air Force Base in California using a Delta II rocket. It is equipped with the Enhanced Thematic Mapper Plus (ETM+) sensor, which represents an advancement over previous models. Key features of Landsat 7 include a panchromatic band with 15-meter spatial resolution, an onboard full aperture solar calibrator, five percent absolute radiometric calibration, and a thermal infrared channel offering a four-fold improvement in spatial resolution compared to the Thematic Mapper (TM) (<https://www.usgs.gov/>). The unsupervised classification of this image helped in understanding the extent of rubber plantations in the district during the year 2001. The results indicate that

the area under rubber plantations in the Kottayam district was 21147.8 ha in 2001. This area is gradually increased to 125591 ha in 2023.

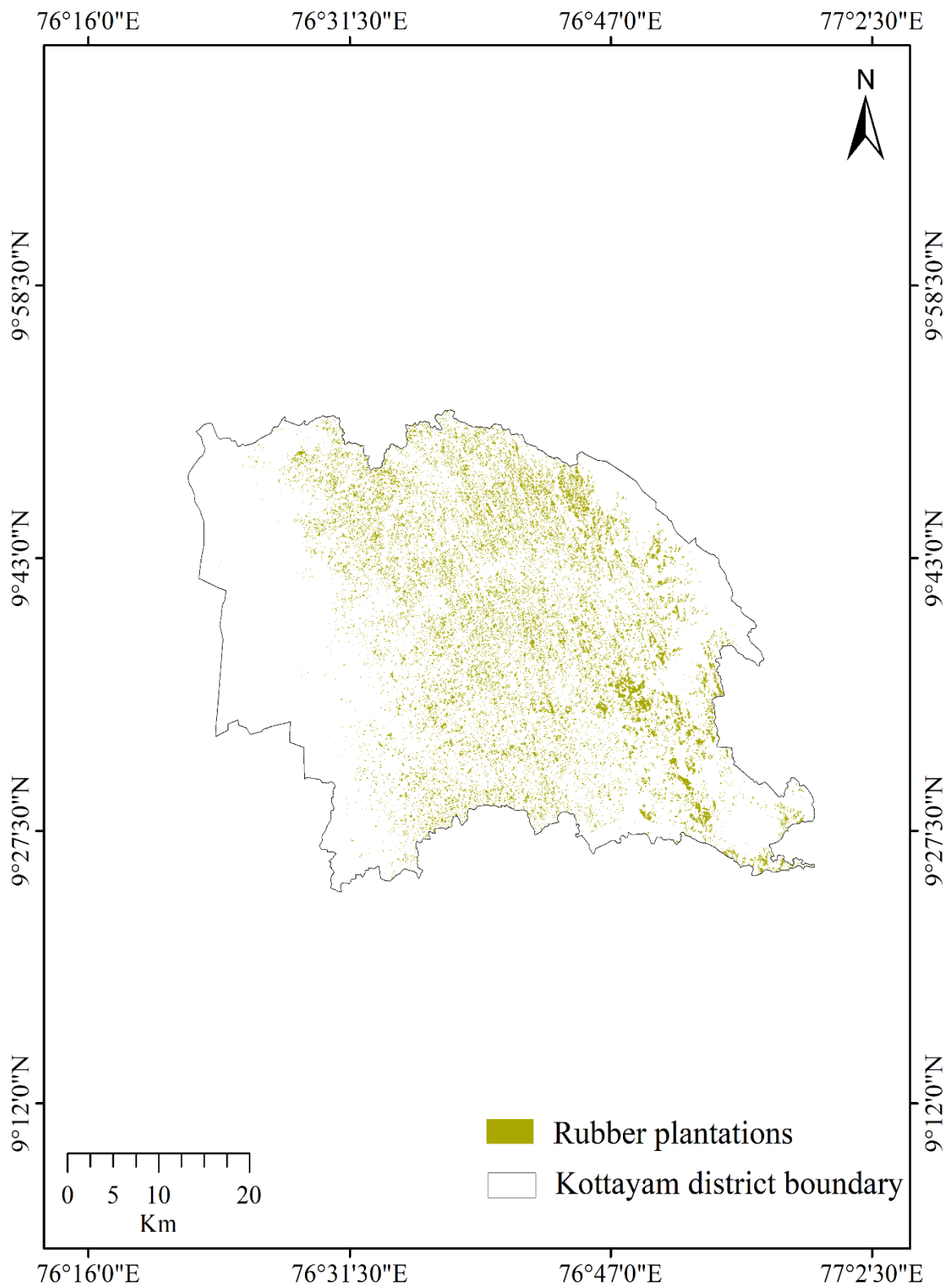


Figure 15: Map representing rubber plantations for the year 2001

4.4 Estimation of Above Ground Biomass (AGB) and Carbon Stock in the study area

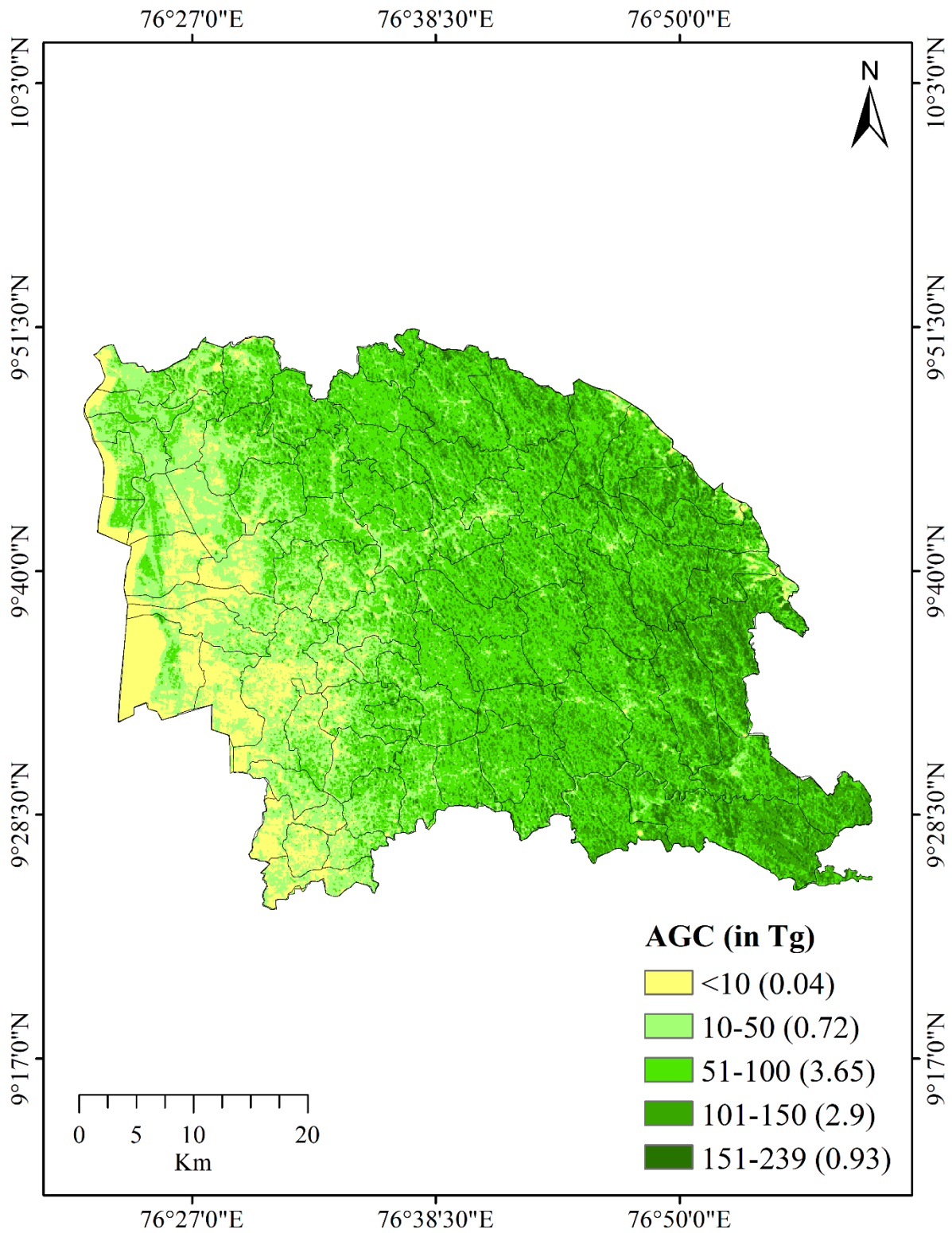


Figure 16: Map representing AGC in 5 classes

The estimation of AGB and carbon stock is critical in the context of climate change. We have estimated the carbon stock distributed for the entire study area using the AGB data of the year 2018. The Santoro has AGB data for the forest pixels for the year 2018. From this we can understand the carbon sequestration capacity of the area. We have classified the AGB according to five classes and estimated the carbon stock for each class. The total carbon stock estimated for the entire study area is found to be 8.3 teragrams. Out of this, less than 10 classes show 0.04 Tg, 10-50 shows 0.72 Tg, 51-100 class shows 3.65 Tg, 101-150 shows 2.9 Tg, 151-239 class shows 0.93 Tg. The 51-100 class holds more carbon which includes rubber monoculture.

Plantations with high standing age will hold more carbon. Based on the field observation and surveys conducted on the rubber estates in the Kottayam district we concluded that most of the rubber monocultures in the district are having more than 20 years of age. These rubber plantations with more standing age can hold more carbon which reflects their high carbon sequestration rate. The rubber plantations were not harvesting due to the reduction in the rubber prices and labour shortage which resulted in untapped rubber with more than 30 years of age. The tapping labor shortage affecting the predominant rubber smallholder sector in Kerala is characterized by its complex dimensions and the varied responses from stakeholders. This shortage is often analyzed as a series of supply-side issues, without fully considering its unique technical, organizational, structural, demographic, gender-related aspects, and the wage payment system (Kadavil, 2012). In recent years, the rubber market has experienced extreme price volatility, with declining rubber prices causing natural rubber production in the country to hit its lowest levels. The study found that prices have dropped so significantly that rubber growers are unable to pay their workers, leading to decreased rubber production and a decline in the standard of living for rubber farmers in Kerala (Karunakaran, 2017).

According to the study by (Pasha et al., 2023) the total carbon stock calculated for all age group rubber plantations was found to be 2.8 Tg. This is because the Tripura state is having less rubber plantations and most of them are less than 10 years of age. Tripura has recently become India's second-largest rubber-producing state after Kerala, thanks to supportive policies and rising demand for rubber. The data shows a substantial growth in rubber plantations in Tripura, expanding from 3.2 thousand hectares in 1990 to approximately 63.8 thousand hectares in 2010, and further increasing to about 93.4 thousand hectares by 2021. During these periods, the Above Ground Biomass (AGB) for natural rubber was recorded at 19.06 thousand tonnes, 693.2 thousand tonnes, and 6007.8 thousand tonnes, respectively. Since the Forest Survey of India (FSI) does not separately categorize rubber plantations, they are

included under forest cover. However, indirect insights can be gained from the FSI change matrix, which shows young plantations being converted from non-forest/scrub to open forest. Future growth in plantations is likely to be classified as transitioning from open to moderately dense forest. The change matrix data reveals that Tripura has experienced a loss of 1306 square kilometres of forest area over the past two decades, with about 327 square kilometres lost between 2015 and 2021. Of this deforestation, 235.21 square kilometres (72%) was attributed to the loss of native deciduous forest. In the case of Kottayam, the district holds 56.93% of rubber plantations with respect to the total geographical area of the Kottayam district and most of them are mature ones which will result in higher carbon stock rate.

4.5 Estimation of vegetation type composition

The total vegetation in the Kottayam district is classified as natural forest, native plantations and non-native plantations. It is estimated that the area under natural forest is 5183 Ha and area falls under native plantations which is the teak monoculture is 4428 Ha and the remaining non-native plantations which are rubber monoculture is found to be 1,25,591 Ha. Out of the total vegetation area 93 % comes under rubber monoculture that is non-native plantations and 3 % falls under teak plantations namely native plantations and natural forest constitutes 4 % with respect to the total vegetation in the study area. The literature survey reveals that there exists a large deviation between native forest, non-native monocultures and tree cover. Hence it is important to discriminate to understand biomass and biodiversity.

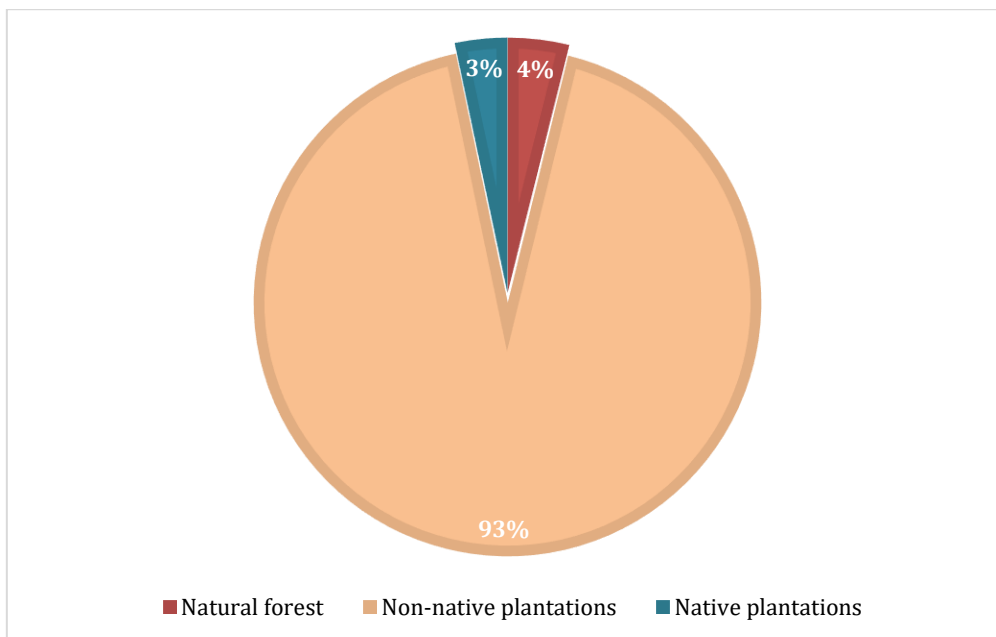


Figure 17: percentage of total vegetation in the study area

4.6 Normalized Difference Vegetation Index (NDVI)

To evaluate the expansion of rubber plantations in the Kottayam district, the NDVI difference between two distinct years was calculated. This calculation helps in determining the land use land cover changes in the area, which is critical in monitoring the impacts of expansion of rubber plantations. We can see that there is no significant increase or decrease in the vegetation cover because most of the expansion happened from agricultural land and forest ecosystems.

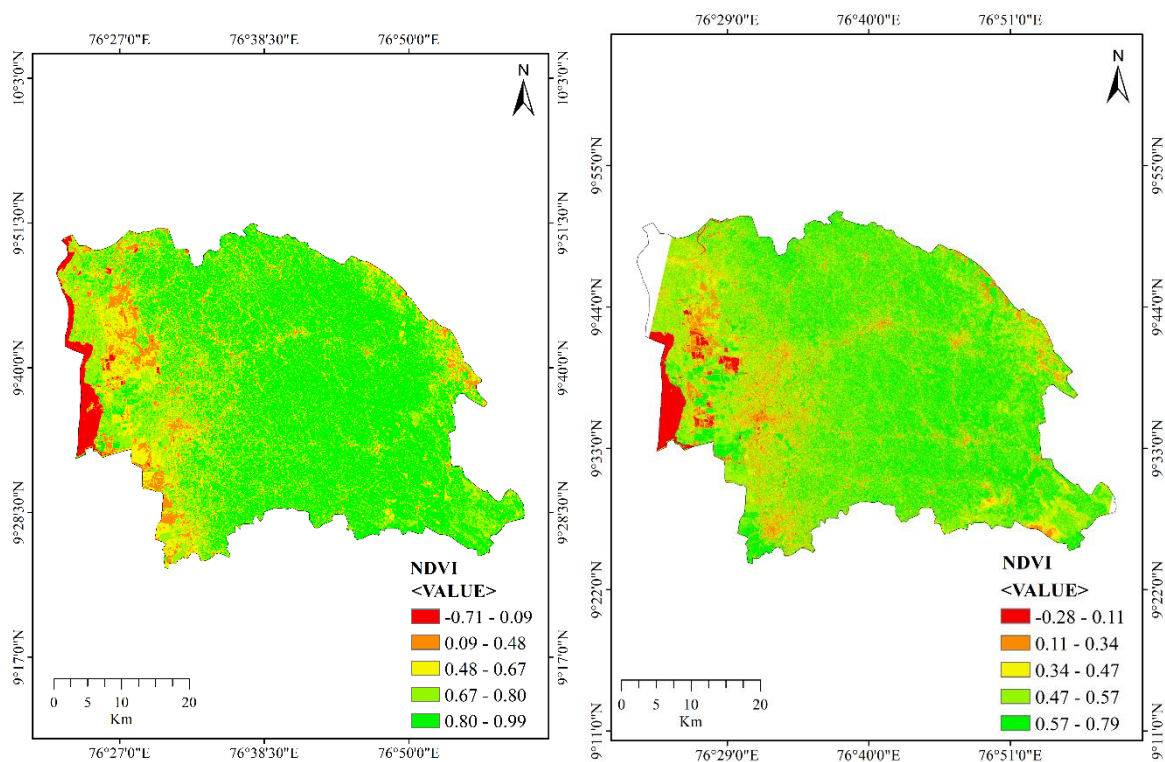


Figure 18: NDVI map showing the dynamics in the water and forests for the year 2001 and 2023

4.7 Analysing the annual rainfall patterns in the Kottayam district (1901-2021)

Understanding the trend of rainfall and its impacts on forest ecosystems is critical for effective conservation initiatives and environment management. The graph reveals the long-term trend in the annual rainfall in Kottayam district from 1901-2021. Understanding rainfall variability is essential for forest ecosystem management thereby conserving biodiversity and for future climate change studies. We can see that there is variability or fluctuations in the

rainfall pattern from the 1970s to the present compared to the normal rainfall in the district. The trend of rainfall will affect the production of crops in the district. Inadequate rainfall patterns can lead to drought and impact the yield and quality of the crops. However excessive rainfall can result in flooding, soil erosion, and water logging and will damage the crops. Long-term fluctuations in the rainfall can affect the water availability which will result in poor irrigation. Changes in rainfall intensity and frequency can increase the risk of flooding leading to biodiversity loss. Understanding the impacts of inadequate rainfall in the Kottayam district is necessary for developing risk management strategies for ensuring sustainable development for the region.

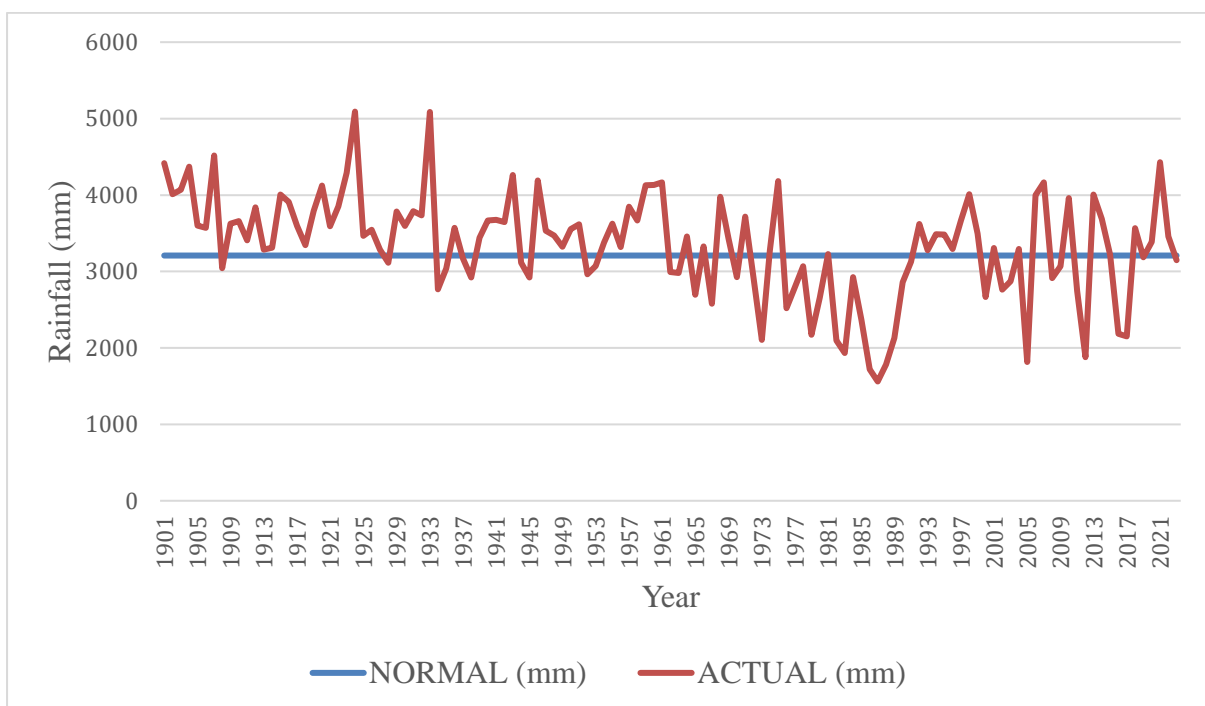


Figure 19: Graph showing rainfall trend in Kottayam district (1901-2021) (source: WRIS, <https://indiawris.gov.in/>)

Seasonal variations in rainfall significantly impact soil water availability, crucial for crop production. Recent changes in rainfall distribution, along with fluctuations and irregular patterns, have been reported to decrease crop yields. This has become a major concern for both farmers and policymakers, posing a threat to food security (Kurukulasuriya et al., 2013). For the past few years, Kerala has been witnessing climate aberrations in the form of extreme

rainfall, temperature changes, storms etc. Kottayam is the district which does not have much difference in their coefficient of rainfall variation (Anil et al., 2022).

Study site – 2

This study was primarily focussed on the anthropogenic impacts mainly the Tuirial hydroelectric project carried out in the Pualreng Wildlife Sanctuary (PWS) and the spatiotemporal monitoring of tree loss that happened due to this project in the past two decades. This study aims to evaluate the impact on biodiversity. It reveals a significant loss of forest cover in the PWS due to the infrastructure development. Understanding the cause and extent of tree loss is critical for the conservation of the protected area. Through this study, we can identify the high-impacted areas and ensure management practices to protect the biodiversity.

4.8 Infrastructure driven forest loss in the Pualreng Wildlife Sanctuary (2001-2022)

It mainly focuses on monitoring the forest loss that happened in the Pualreng Wildlife Sanctuary which is a part of the Indo-Burma Biodiversity Hotspot (IBH). The major factor contributing to the forest loss is the infrastructure development that is the dam construction. In 2014, the construction of the dam caused a rise in the water level which resulted in the area being flooded. Gradually the forested land becomes inundated with water. This gradual increase in water after the dam construction in 2014 caused the decay of trees which also resulted in the loss of biodiversity. The area becomes gradually submerged in the following years. To better understand the forest loss in the protected area we have estimated the tree loss area for every year in the last two decades from the tree loss data.

The map illustrates the spatial distribution of tree loss within the protected area over the two decades. It indicates that the area nearer to the water body has been lost over the years. This will be mainly due to the submergence of land and deforestation that occurred during the construction of the dam. The impact of deforestation will adversely affect biodiversity and also cause changes in the AGB which will result in reducing the carbon sequestration rate.

From this study, it is indicating that the highest maximum forest loss happened during the year 2017. Looking at the trend over the decades, there is a notable increase in forest loss which leads to biodiversity loss and habitat fragmentation. The year-wise study reveals that the primary forest loss is due to the Tuirial Hydroelectric Project. However, the results indicate that 10.42 % of tree cover is lost with respect to the geographical area of the Pualreng Wildlife Sanctuary.

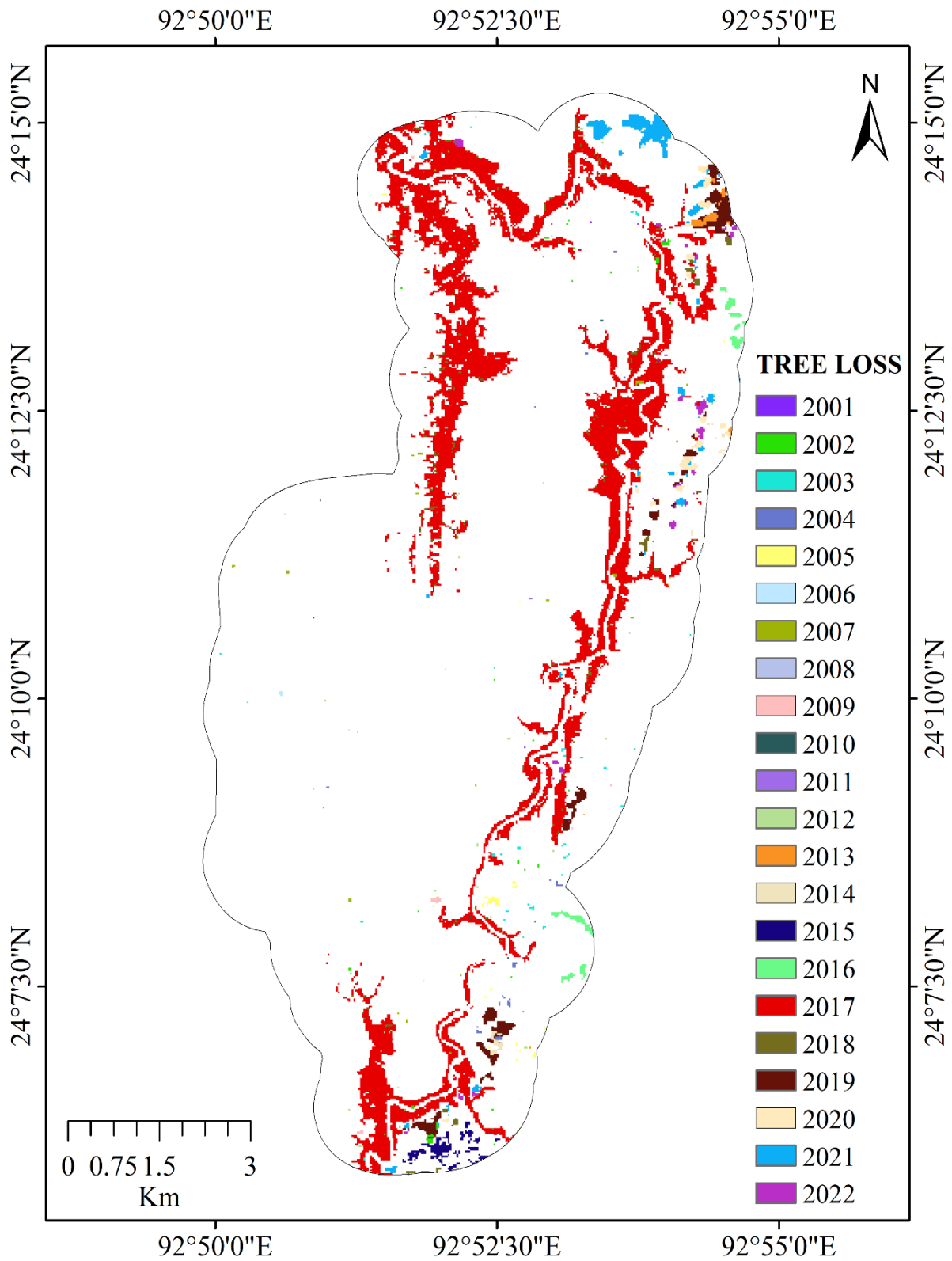


Figure 20: Map showing forest loss in the PWS (2001-2022)

4.9 Annual tree cover loss in the Pualreng Wildlife Sanctuary (2001-2022)

Annual tree loss data from 2001-2022 reveal that in the Pualreng Wildlife Sanctuary, a total of 542.14 ha of area of land has been lost. However, the significant forest loss caused in the year 2017 is due to the infrastructure development that is the Tuirial hydroelectric project. The decline in forest cover was 0.32 ha of area in 2001 which was increased to 1.68 ha of area in 2022. In the first decade, the forest cover loss has been gradually increased from 0.32 ha of area to 0.40 ha of area. The highest recorded forest cover loss happened in 2017 which was about 516.03 ha of area. In the second decade, the forest cover loss decreased from 0.40 ha of area in 2011 to 0.32 ha of area in 2020 and further increased to 1.68 ha of area in 2022.

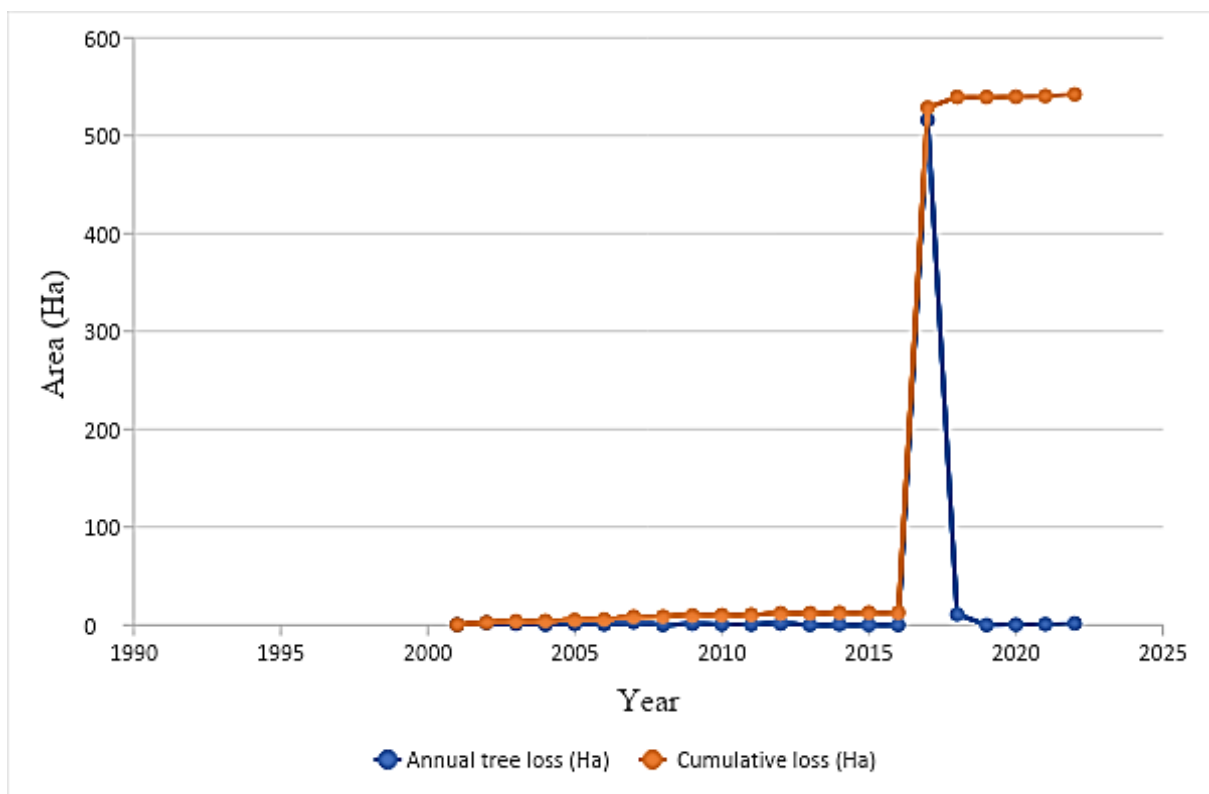


Figure 21: Graph showing annual tree cover loss and the cumulative loss in the protected area

The graph represents the area of forest cover that is lost within the protected area as a result of the infrastructure development. It shows an abrupt increase in the trend for the year 2017 due to the submergence of land caused by the dam construction. It is indicating that 10.42 % of the total geographical area, that is about 50 Km², was lost during the two decades. The cumulative loss, that is the total loss of forest cover over a specific period typically over two decades reflects the yearly impact of the submergence and provides a broader view of the long-term trend in the forest loss happening in the protected area.

Table 5: Table showing year wise annual tree cover loss and cumulative loss

Year	Annual tree loss Area (Ha)	Cumulative loss area (Ha)
2001	0.32	0.32
2002	2.32	2.64
2003	1.28	3.91
2004	0.32	4.23
2005	0.96	5.19
2006	0.56	5.75
2007	2.80	8.55
2008	0.08	8.63
2009	1.12	9.74
2010	0.40	10.14
2011	0.40	10.54
2012	1.44	11.98
2013	0.08	12.06
2014	0.56	12.62
2015	0.00	12.62
2016	0.00	12.62
2017	516.03	528.64
2018	10.78	539.43
2019	0.00	539.43
2020	0.32	539.75
2021	0.72	540.46
2022	1.68	542.14

4.10 Normalized Difference Vegetation Index (NDVI)

To monitor the land use/land cover change we have calculated the NDVI for two consecutive years. This will help in evaluating the impacts caused by the infrastructure development in the Wildlife Sanctuary. We can see that there is a drastic decrease in the vegetation cover along the sides of the waterbody in the year 2022 compared to the year 2001.

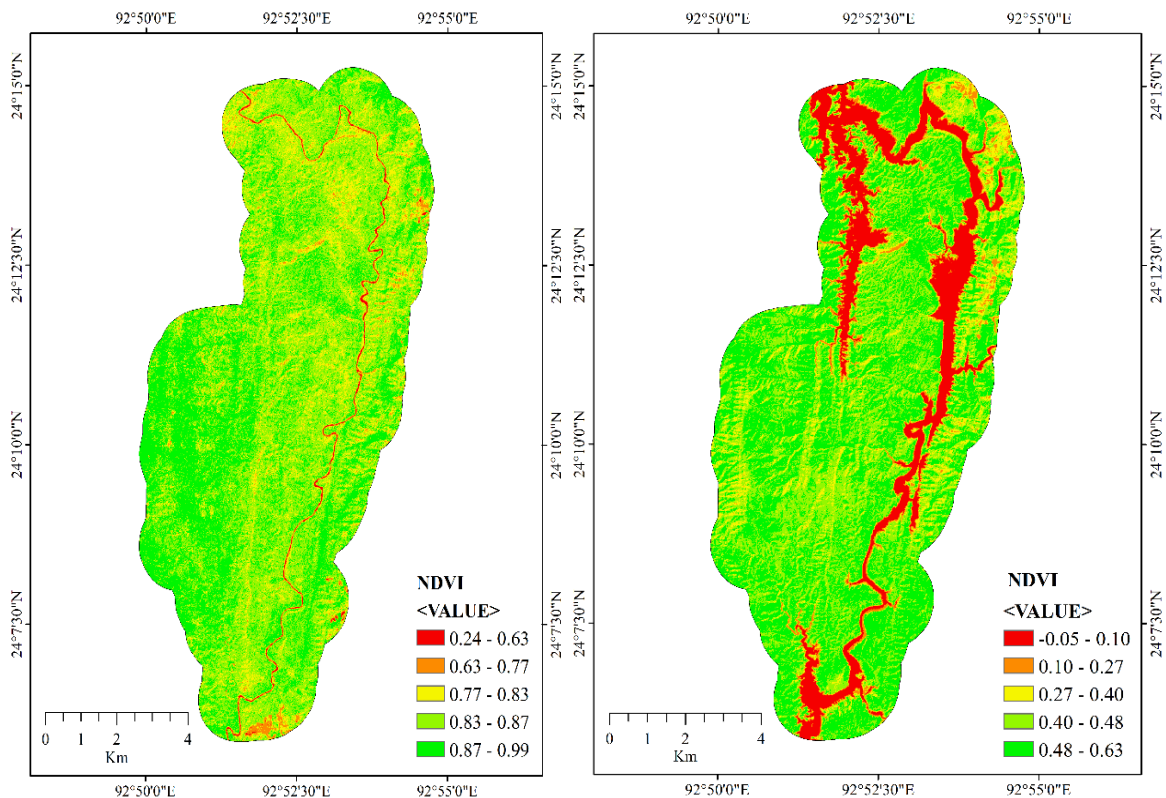


Figure 22: NDVI map showing the dynamics in the water and forests for the year 2016 and 2022

4.11 Analysing the rainfall pattern in the Kolasib district

Analysing the rainfall trend from 1901 to 2021 in the Kolasib district offers valuable insights into the long-term climatic variability of the region. The graph provides an overview of the Kolasib district's overall rainfall patterns over the years. The trendline shows annual rainfall amounts over consecutive years. It is clearly indicating the variability or fluctuation in the annual rainfall trend from the 1960s to the present year. This could include periods of above-average rainfall (wet years), below-average rainfall (dry years), or irregular patterns of rainfall distribution within the Kolasib district. It is important that the continued monitoring and research will lead to better understanding and adaptation to changing rainfall patterns in

the region. Changes in precipitation lead to ecological shifts affecting tree growth conditions. Both biomass and species richness tend to increase with mean annual precipitation, with these effects stabilizing over time (Hiltner et al., 2016).

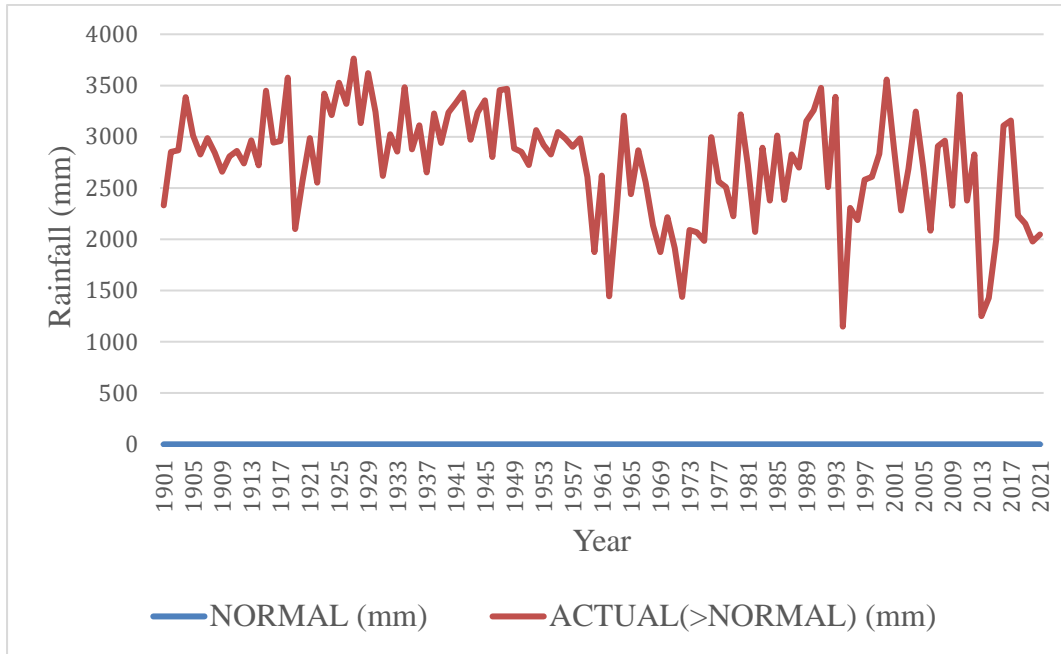


Figure 23: Graph showing rainfall trend in Kolasib district (1901-2021) (source: WRIS, <https://indiawris.gov.in/>)

4.12 Discussion

Rubber is a significant commercial crop mainly cultivated in Kerala (Chattopadhyay, 2021). Kerala is the highest rubber-producing state in the country, while Kottayam is the number one among the states. However, according to the definition of forest by FSI, 49.82 km² of the geographical area is under forest. The present study shows the majority of the vegetation is under rubber plantations. Only very few percent of natural forest exist in the district, in which some 3% area consists of teak plantations. So, there is a misunderstanding between forest cover, tree cover and natural forest. It is important to discriminate between vegetation type, natural forest and native forest for the better understanding of biodiversity and biomass under the changing climate.

Plant age plays a direct relation with biomass and an important role in understanding the c-stock (Pasha, and Dadhwal, 2023; Pasha et al., 2023). In this context, the study area is predominantly with the rubber plantations. These rubber plantations are distributed to different age groups. However, literature surveys reveal that the studies show the age of the plantation

under-represented. Understanding the mean age of a planted or managed ecosystem is a growing field of research.

Characterizing various age groups in a plantation would help the need for skilled, semi-skilled, and unskilled labour requirements as Kerala requires a shortage of skilled labour. The generated database from this study serves as biomass, biodiversity studies and also socioeconomic conditions of livelihood of the people. It will be linked to the SDGs 1, 13 and 15.

Every plantation has its harvesting cycle. For instance, Eucalyptus has 8 years and rubber has 30 years due to its low productivity. So, harvesting and replanting is a common management practice throughout the world. In this case, mature or old low-productive plantations have been harvested or uprooted followed by replanting. So, the majority of the studies treat this process as deforestation. However, this is tree removal, not deforestation. So, to address all above-mentioned concerns, mapping and characterizing the age is critical for environmental, socioeconomic, sustainability and climate change.

In the PWS, the major factor contributing to the tree loss is submergence caused by the Tuirial hydroelectric project. The project came into existence in the year 2014. A gradual increase in the water causes the submergence of land which leads to the forest loss in the protected area. The forest loss in the protected area causes habitat loss or fragmentation which will result in the extinction of endemic species in the area.

The protected area is home to several notable birds and wild animals, including the Great Indian Hornbill (Vapual), Wreathed Hornbill (Kawlhawk), Pied Hornbill (Vahai), Khaleej Pheasant (Vahrit), Bhutan Peacock Pheasant (Varihaw), Red Junglefowl (Ramar), White-Cheeked Partridge (Varung), and arboreal species like the Hoolock Gibbon (Hauhuk), Slow Loris (Sahuai), Common Langur (Ngau), and Rhesus Macaque. Additionally, it houses the Himalayan Black Bear (Savawm), Leopard (Keite), Sambar (SDazuk), Barking Deer (Sakhi), Binturong (Zamphu), and Chinese Pangolin (Saphu) (<https://forest.mizoram.gov.in/>). These endemic species will be impacted due to habitat loss or fragmentation. The fragmentation of the forested areas disrupts the ecosystem of the protected area. Ensuring mitigation measures are crucial to minimize the environmental impacts caused by the dam construction. This study highlights the increasing impacts of infrastructure development on forested ecosystems especially in the ecologically sensitive area. There is a need for future research and actions to the continuous monitoring of the risks posed by infrastructure development.

CHAPTER-5

CONCLUSIONS AND RECOMMENDATIONS

Both study areas have undergone significant land cover changes due to human activities. The establishment of rubber monoculture plantations in the natural landscape, along with their typical harvesting cycle, has impacted aboveground biomass (AGB) and carbon stocks in Kottayam. Additionally, the Pualreng Wildlife Sanctuary has been affected by infrastructure development, specifically the Tuirial hydroelectric project, resulting in the submergence of a significant amount of tropical forest and impacting biomass and carbon stock.

The Pualreng Wildlife Sanctuary is part of the Indo-Burma Biodiversity Hotspot in the northeast region and hosts endemic flora and fauna. Remote sensing observations indicate forest loss in the study area. The present study recommends redesigning the protected area and establishing suitable habitats for wildlife and the need for detailed monitoring using high-resolution satellite data to understand small-scale disturbances. The findings reveal significant tree loss in the sanctuary due to deforestation and land submergence, affecting biodiversity. Habitat fragmentation has cascading effects on flora and fauna, impacting the native forest. Reforestation efforts are essential to restore the protected area's habitat, and enhancing conservation practices is critical to reduce further deforestation in the region. Comprehensive monitoring and evaluation of the ecosystem are necessary to understand the long-term impacts of the Tuirial hydroelectric project on the protected area and its community.

In the Kottayam district, the expansion of mono-plantations has led to the conversion of other land cover or ecosystems into rubber plantations. This conversion results in habitat fragmentation and biodiversity loss. Natural forests play a crucial role in carbon storage, making environmental management and conservation initiatives critical for maintaining carbon sequestration capacity in the region. Converting natural landscapes to rubber plantations leads to biodiversity loss and climate regulation challenges. The mature rubber trees have a high carbon sequestration capacity; however, they will harvest around 30-35 years due to low latex production. This study recommends comprehensive land management approaches. Continued monitoring of land cover changes and rubber plantation expansion in the district is necessary to assess the long-term impacts on carbon stocks and biodiversity. We recommend an age-based mapping of NR plantations for improved c-stock.

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**VEGETATION AND FOREST CARBON DYNAMICS IN RELATION
TO ANTHROPOGENIC IMPACTS AND CLIMATE VARIABILITY AT
SELECTED SITES IN INDIA**

by

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ABSTRACT OF THESIS

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ABSTRACT

Human activities, particularly monoculture plantations and infrastructure development, significantly alter natural landscapes. Monitoring these activities in global biodiversity hotspots is crucial. This study focuses on spatiotemporal changes in vegetation and carbon dynamics in two distinct regions: Kottayam district in Kerala, and the Pualreng Wildlife Sanctuary (PWS) in Mizoram. The primary objective of the first study was to monitor the expansion of rubber plantations in Kottayam, Kerala, which is the state's highest rubber-producing district. Mapping and estimating carbon stocks are essential to understand the environmental impacts resulting from rubber plantation growth. Remote sensing technologies, including Landsat 7 and LISS-IV satellite images and topographical maps, were used to identify spatiotemporal dynamics and assess carbon stock. Forest cover dynamics were evaluated using the Forest Survey of India (FSI) and multi-temporal data, revealing that rubber plantations now cover 56.93% of the district's total geographical area. Additionally, 4.48% of the area consists of natural forests, including teak monoculture (2.01%). Estimating aboveground biomass (AGB) and carbon stock is critical for climate change considerations. The study estimated a total carbon storage of 8.3 teragrams for the entire study area in 2018. The second study focused on anthropogenic impacts, specifically the Tuirial hydroelectric project within Pualreng Wildlife Sanctuary (PWS), Mizoram. Using remote sensing techniques and satellite imagery from Landsat and Sentinel-2A, the study analysed tree loss over the past two decades. The results revealed a significant reduction in forest cover due to infrastructure development, leading to habitat fragmentation and biodiversity loss. Recommendations include environmental assessments and conservation initiatives to mitigate the impacts caused by the Tuirial hydroelectric project on PWS. Age-based approach for enhanced C-stock for rubber plantations. Understanding these dynamics and implementing conservation measures are critical for maintaining ecosystem health and resilience in these regions.

ANNEXURE-1

Field observation

The android-based field survey is helpful for the better understanding of the location and the phenology of the rubber plantations. We can also identify the features like weather, altitude etc. through these types of surveys. The below table shows the age wise rubber plantations and their latitude and longitude from five plots in the Kottayam district.

Table 6: Age wise locations of the rubber plantations

Sl. No	Rubber Age	Longitude	Latitude
1	30-year-old	76.51903534	9.596251488
2	30-year-old	76.51885986	9.596012115
3	30-year-old	76.58487701	9.590121269
4	30-year-old	76.51903534	9.596251488
5	30-year-old	76.58478546	9.590071678
6	30-year-old	76.58472443	9.590067863
7	30-year-old	76.58472443	9.590067863
8	30-year-old	76.58487701	9.590121269
9	30-year-old	76.58487701	9.590121269
10	30-year-old	76.58478546	9.590071678
11	30-year-old	76.58483887	9.590105057
12	30-year-old	76.58461761	9.589980125
13	30-year-old	76.58486938	9.589629173
14	30-year-old	76.58486938	9.589629173
15	30-year-old	76.58472443	9.590067863
16	30-year-old	76.58478546	9.590071678
17	30-year-old	76.58478546	9.590071678
18	30-year-old	76.58472443	9.590067863
19	15-year-old	76.58516693	9.589477539
20	15-year-old	76.58522797	9.589374542
21	15-year-old	76.58473206	9.589976311
22	15-year-old	76.58491516	9.590224266
23	12-year-old	76.58516693	9.589477539

24	12-year-old	76.58518219	9.589458466
25	12-year-old	76.58505249	9.589568138
26	12-year-old	76.58516693	9.589477539
27	12-year-old	76.58518219	9.589458466
28	12-year-old	76.58494568	9.59025383
29	10-year-old	76.58447266	9.590646744
30	10-year-old	76.58447266	9.590646744
31	10-year-old	76.58435822	9.590510368
32	8-year-old	76.58435059	9.59052372
33	8-year-old	76.58438873	9.59058857
34	8-year-old	76.58449554	9.590595245
35	8-year-old	76.58448792	9.590653419
36	8-year-old	76.58447266	9.590646744
37	8-year-old	76.58448792	9.590653419
38	5-year-old	76.58449554	9.590657234
39	5-year-old	76.58427429	9.590498924
40	5-year-old	76.58428955	9.590501785
41	5-year-old	76.58428955	9.590513229
42	5-year-old	76.58433533	9.590499878
43	5-year-old	76.58449554	9.590657234
44	5-year-old	76.58449554	9.590657234
45	5-year-old	76.58449554	9.590657234

Table 7: Girth measured for each age group.

Age group	Average Girth (in cm)
35-year-old rubber	189
30-year-old rubber	155
20-year-old rubber	135
15-year-old rubber	114
12-year-old rubber	99
10-year-old rubber	95
9-year-old rubber	70
8-year-old rubber	56
7-year-old rubber	65
5-year-old rubber	46



Figure 24: a) Photograph showing 20-year-old rubber b) 15-year-old rubber c) 9-year-old rubber d) 9-year-old rubber e) 30-year-old rubber f) 35-year-old rubber g) 10-year-old rubber

These photographs of the rubber plantations were taken from the five plots in the study area. These visually depict the different stages of the rubber plantations from the field site. These photographs are shown to represent the young and mature tapped rubber plantations in the site. The young plantations are those who never reached maturity. The mature plantations are the tapped rubber that produce high amounts of latex. The average girth was also measured for each of the age groups.