ASSESSMENT OF NET ECOSYSTEM PRODUCTION AND CARBON DYNAMICS IN SELECTED TREE PLANTATIONS OF MIZORAM

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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MZU REGISTRATION NO.: 1900110

Ph.D. REGISTRATION NO.: MZU/Ph.D./1332 of 29.07.2019

DEPARTMENT OF FORESTRY

SCHOOL OF EARTH SCIENCE AND NATURAL RESOURCE MANAGEMENT

MARCH 2025

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BY

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Submitted

In partial fulfillment of the requirement of the Degree of Doctor of Philosophy in Forestry of Mizoram University, Aizawl.

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CERT IFICAT E

This is to certify that the thesis entitled, ―Assessment of Net Ecosystem Production and Carbon Dynamics in Selected Tree Plantations of Mizoram‖ submitted by Ms. Lalrempuii Hrahsel to the Department of Forestry, Mizoram University, Aizawl, for the award of the degree of Doctor of Philosophy in Forestry embodies the record of original investigation carried out by her under my supervision. I further certify that Ms. Lalrempuii Hrahsel has fulfilled all the criteria prescribed by UGC and the conditions laid down in the Ph.D. regulations of the Mizoram University. The thesis as whole nor any part of it has not been submitted earlier to any university or institute for the award of any degree and the thesis presented is worthy of being considered for the award of the Ph.D. Degree.

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DECLARAT ION

MIZORAM UNIVERSITY

MARCH, 2025

I **LALREMPUII HRAHSEL,** hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of this thesis did not form basis of the award of any previous degree to me or to do the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/Institute.

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ACKNOWLEDGMENT

I would like to express my deep gratitude to all those who played a role in the successful completion of this thesis.

First and foremost, I would like to express my sincere gratitude to my supervisor, Prof. Uttam Kumar Sahoo, Department of Forestry, Mizoram University, for his invaluable support and encouragement throughout my PhD journey. His insightful feedback, patience, and unwavering belief in my work have been instrumental in shaping this research. His guidance throughout this journey has been immense and I am fortunate to have a supervisor who is not only my mentor but also a source of inspiration, making this journey both enriching and fulfilling.

I am profoundly grateful to Prof. Kalidas Upadhyaya for his generous support and willingness to share his expertise whenever I needed guidance. His kindness and invaluable insights have greatly contributed to my research. I also extend my sincere appreciation to all the professors in the Department of Forestry at Mizoram University for their dedication, guidance, and constant availability, which have enriched my academic journey.

I also wish to thank my fellow research scholars for their moral support and enriching discussions. I am deeply grateful to Dr. Uttam Thangjam, Dr. Pentile Thong, and Dr. Alice Kenye for their constant guidance, support, and words of encouragement. Their wisdom and insights have been a source of reassurance throughout this journey. I would also like to extend my heartfelt appreciation to Mrs. Baby Lalhmangaihzuali, whose unwavering support and selflessness have been truly invaluable. I take this opportunity to express my gratitude to everyone who, directly or indirectly, contributed to the completion of this work. Though I cannot name everyone individually, please know that your support and kindness are deeply appreciated. I am fortunate to have met so many wonderful people in the Department of Forestry, Mizoram University.

I am also thankful to the owners and caretakers who have allowed me to use their plantations as a study site. My deepest gratitude to Mr R. Tlanghmingthanga, ex- Minister and his family for their generosity as well as care shown to my research work. I would also like to express my gratitude to Mr. K. Lalchhuanmawia, whose guidance was instrumental in helping me identify my research sites and guiding me during my field visits.

To my family, your unwavering love, encouragement, and sacrifices have been my greatest source of strength. Without your constant support, this journey would not have been possible. My heartfelt gratitude goes to my parents, Prof. Vanlalchhawna and Prof. Sanny Tochhawng, whose love and support have shaped me into the person I am today. I am also deeply thankful to my brother, Lalmuanfela Hrahsel, who accompanied me on all my fieldwork; without his help, conducting my research would have been far more challenging. Additionally, I extend my sincere appreciation to Mr. Zodinsanga and his friends for their invaluable assistance during my fieldwork. I also would like to thank my extremely patient friends, PC Lalrempuia and C. Lalnunzami, for always lending me an ear and a shoulder to rely on.

Finally, I thank God Almighty for His blessings.

This thesis is dedicated to all who believe in the power of knowledge and research to make a difference.

(LALREMPUII HRAHSEL)

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CHAPTER I- GENERAL INTRODUCTION

1.1. Climate change mitigation and carbon sequestration

Climate change impacts have been escalating in a rapid way such that its mitigation and abatement strategies are now deemed a necessity. Climate change mitigation is the reduction of greenhouse gases (GHGs) whereas abatement focuses on limiting the rise in global temperature. Numerous approaches such as carbon sequestration, transition to clean energy sources and international environmental agreements are a key role in addressing this global challenge (Fawzy et al., 2020; Singh, 2024). Global warming and climate change have caused concerns on the study of global carbon storage in addition to carbon balance (Kabir et al., 2023). Forest plantation comprised of 7% of the world‘s forest area and approximately 5 million hectares per year have expanded; this shows that it will have a critical impact on global carbon cycling (J. Zhang et al., 2011; FAO, 2022). Half of the global forest area is being represented by tropical forests and are regarded to be the largest reservoir of carbon in terrestrial ecosystem (Nogueira et al., 2015). One-third of the earth is covered by forests, consisting of 80% total aboveground carbon and 40% belowground carbon, which signify that forests have an important role in the global carbon cycle (Meena et al., 2019).

Carbon sequestration is the active absorption of carbon dioxide present in the atmosphere and through photosynthesis, it is stored in the biomass of trees and plants (Kowalska et al., 2020). It plays a critical role in combating climate change and land degradation within the framework of the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC objective is to mitigate rising atmospheric carbon dioxide (CO_2) levels by converting greenhouse gases into organic matter (Arnalds, 2004) and helps in providing a platform for international cooperation and promoting sustainable solutions to address climate change. The UNFCCC emphasized the importance of tree plantation in mitigating climate change and achieving carbon neutrality. Tree plantations have the potential to sequester carbon dioxide (CO_2) from the atmosphere and store carbon, making them an effective strategy for climate change mitigation (Kongsager et al., 2013; Kothandaraman et al., 2022).

The Kyoto Protocol, under the UNFCCC, promotes afforestation and reforestation as means to increase wood production and reduce greenhouse gas emissions (Oluwadare, 2011)). It recognizes carbon sequestration as an incentive for restoring degraded lands and enhancing soil conservation efforts (Arnalds, 2002). Additionally, tree plantations can provide various environmental as well as socio-economic benefits, such as conserving soil, supporting biodiversity, providing renewable energy along with employment opportunities (Mukhlis et al., 2022) However, it is crucial to ensure that tree plantations are well-planned and integrated into climate action plans to avoid negative environmental impacts (Péroches et al., 2022) Alternative plantation models that involve diverse stakeholders and consider multiple objectives, such as carbon storage, biodiversity conservation, and rural livelihoods, should be promoted. Carbon capture and storage may pose as a challenge in terms of liability and cross-border activities (Bode & Jung, 2005), hence natural carbon sequestration by forests has shown a significant potential. Global forests can act as a substantial carbon sink and their capacity is increasing over recent decades (Ncipha & Sivakumar, 2019).

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, the Agriculture, Forestry, and Other Land Use (AFOLU) sector contributed between 13% and 21% of global anthropogenic greenhouse gas (GHG) emissions from 2010 to 2019. During this period, estimated anthropogenic net CO_2 emissions from AFOLU were approximately +5.9 ± 4.1 gigatonnes of CO_2 equivalent per year, with the trend remaining uncertain (IPCC, 2023a). Land use changes are the primary drivers of net CO_2 fluxes in the AFOLU sector, with deforestation accounting for 45% of total AFOLU emissions. Beyond its role as a net carbon sink and GHG source, land significantly influences the climate through effects on albedo, evapotranspiration, and aerosol loading, which involves the emission of volatile organic compounds (IPCC, 2023b).

Forests are globally distributed covering 31% of the land and they are the largest pool of biodiversity and carbon stock (Mahajan et al., 2023). Yet, the rapid climate change and accelerating anthropogenic activities have reduced the forest area by deforestation and changes in land use (IPCC, 2019). An estimated 420 million hectares of forests have reportedly been lost due to of deforestation and the rate was evaluated to be 10 M ha per year since 1990 and 2020 (FAO, 2022). The demanding agricultural practices such as cattle ranching, soybean cultivation and oil palm are still some of the main reasons for forest loss (FAO, 2022). The past decades have shown a high interest in the impact of different land use on the diversity of trees and other ecosystem properties (Hansen et al., 2004).

Forests provide a mitigation strategy in reduction of global warming (Schimel, et al., 2001). The woody biomass of forests is expected to store more carbon compared to other terrestrial ecosystems, as well as accumulate carbon with long residence time (Watson, et al., 2000; Lorenz, 2009). According to Forest Resources Assessment Report (2015) , the world‘s forest store an estimated amount of 296 Gt of carbon in aboveground and belowground biomass (FAO, 2016). Over the past 25 years, carbon sequestration in forests has gone down by approximately 17.4 Gt which is equal to 697 million tonnes per year or about 2.5 Gt of carbon dioxide (India State of Forest Report, 2019). Hence, forest ecosystems have been the primary focus for developing mitigation strategies necessitating immediate conservative measures towards climate change (Mackey et al., 2020).

India‘s green cover has increased by 0.56% since 2018 (Union Government of India, 2019). The total green cover in India as of 2019 was 24.6% of its geographical area with the total forest cover reported to be 21.67% of the country‘s geographical area (Union Government of India, 2019). Forests cover account 66% of the total geographical area in North east India (Ministry of Environment, Forests and Climate Change, 2017) and these forests have an important influence on the carbon balance. As per the Forest Survey of India, (2023), Mizoram experienced one of the highest increases in forest cover and also ranked highest among the states with the highest forest cover relative to its total geographical area (85.34%).

In South-east Asia, much of the previous rainforest areas were converted to rubber agroforests and monoculture plantations of oil palm and rubber (Beukema et al., 2007). Rubber and oil palm plantations are the world‘s most rapidly increasing crops (Ahrends et al., 2015; Fitzherbert et al., 2008). Although there are negative aspects of these plantations, they have a vast potential for terrestrial carbon sequestration by accumulating woody biomass (Das et al., 2021). Areca nut was introduced as a significant commercial crop in South-east Asia, with India being the largest producer (Mitra & Devi, 2018) The rapid expansion of Areca plantations in Northeast India is often at the expense of natural forests, raising concerns about environmental sustainability (Barnes et al., 2014). In Mizoram, plantation crops such as areca nut, tea, coconut, etc. have successful growth rate. About 11.56 lakh hectare of land has cultivable potential in Mizoram and around 1.50 lakh hectare is covered under plantations of various crops and trees (Planning & Programme Implementation Department, 2025). Due to the Mizoram Oil Palm (Regulation of Production & Processing) Act. 2004, 3398 hectares of land in Mizoram is under oil palm cultivation (Planning & Programme Implementation Department, 2024). The launching of National Mission on Edible Oils-Oil Palm (NMEO-OP) increased the area under oil palm plantation and the jhum area when compared between 2005-06 and 2022-23 has decreased by 45% due to this initiative (Planning & Programme Implementation Department, 2024).

1.2. Livelihood in Mizoram

In Mizoram, agriculture serves as the primary source of employment for over 70% of the population, who rely on land-based activities for food, livelihoods, and energy. However, the prevalence of unsustainable traditional jhum cultivation practices, has led to significant land degradation, particularly on the region's steep slopes (FAO, 2019). About 44.25% of the GDP comes from the service sector in Mizoram, whereas only 29% and 26.76% is from the industry and agricultural sectors respectively (Directorate of Economics and Statistics, 2022). Approximately 90% of Mizoram's population comprises diverse ethnic minority tribes, often recognized as indigenous peoples, who have traditionally practiced jhum or shifting cultivation. This cultivation, also known as slash-and-burn or swidden agriculture, involves clearing forests, burning debris, and cultivating land for a limited time before allowing it to fallow. This practice is also prevalent in other tropical and subtropical regions, with a significant number of people engaged in it globally, particularly in Asia. Shifting cultivation has been practised in north-eastern states of India for centuries and it has been a traditional agricultural method.

The intervening period between two shifting cultivation is termed the 'Jhum cycle,' and the farmers practicing this method in Mizoram are called Jhumias. The farmers shift their cultivation areas after a complete cycle, which has been a tradition for centuries. Consequently, these farmers abandon these plots and clear new ones for cultivation. The area under shifting cultivation in north-eastern India is significant, with Mizoram having a notable portion of its agricultural land dedicated to this practice. Despite the low production and yield, shifting cultivation remains a vital socio-cultural activity for the farmers. The challenges faced by these farmers include climate variability, soil erosion, and food insecurity. The state of Mizoram has a unique land tenure system where the State Government owns the land. Individuals can convert agricultural land passes into Land Settlement Certificates or 'Patta', which are primarily for residential purposes. In 2011, the state government implemented the New Land Use Policy (NLUP) to formalize forest land titles, which had previously been decentralized and managed under traditional legal frameworks (Bose, 2019). The other objective of NLUP was to provide sustainable livelihood by promoting integrated farming system or tree-based system. In order to replace the pre-existing jhumming cultivation towards a more permanent method of farming, plantation and horticulture are the most viable replacement. Mizoram has a vast potential for cultivating a wide range of crops and this in turn could generate steady income and livelihood for the people.

The potential for plantation-based livelihoods in Mizoram is significant, particularly with the expansion of rubber and oil palm cultivation (Lallianthanga et al., 2014; Bose, 2019; Prasad Sati, 2023). The region's agro-climatic conditions favour such initiatives, offering opportunities for economic development and community resilience. One of the significant plantation-based livelihood in Mizoram is oil palm cultivation due to the state government‘s initiative since 2004 (Lalawmpuia et al., 2020). The Statistical Handbook of Mizoram (2022), published by the Government of Mizoram reported that 37 hectare of land under rubber plantation was owned by the state government, while 2528.7 hectare of rubber plantation is owned by the private sector. Areca nut occupied 21.42 hectare of land and it‘s production was 33.54 Mt with a yield of 1.57 Mt/ha in the year 2021-22. Oil palm plantation in 2020-21 was 740 hectare in Mizoram with no increase in the following year. These plantation-based livelihood is expected to uplift the standard of living for the farmer by enabling them to purchase necessary machineries as well as provide better education for their children. It is also expected to generate employment for the people as well as assure monthly income throughout the year by practicing inter-cropping during the pre-bearing period.

According to Sati (2022), although oil palm may offer a higher income compared to other crops, farmers in Mizoram, still face challenges in management, harvesting as well as market access. The state‘s capital can present abundant opportunities including sustainable rural livelihoods (Sati, 2022), yet the state of Mizoram still lacks the financial and physical capital which lead to under-utilization of natural resources and persistent poverty (Sati & Vangchhia, 2017b). Global tree restoration may possibly store 205 gigatonnes of carbon and mitigate climate change however, climate change could shrink this potential canopy cover by 223 million hectares by 2050 (Bastin et al., 2019). Restoring degraded tropical forests is cost-effective for carbon sequestration and improving habitat for threatened species, while multiple forest types can reduce accumulated carbon by up to 24% (Budiharta et al., 2014). Restoration of forest is more advantageous as it can create involvement and employment to the local people who are undertaking and maintain plantings (Stanturf & Mansourian, 2020).

To address these issues, recommendations include developing forest-based small-scale industries, improving water management, and diversifying crop cultivation (Sati, 2023). Additionally, enhancing financial capabilities and infrastructure development are crucial for harnessing natural capital sustainably and achieving food security (Sati & Vangchhia, 2017a). Balancing economic benefits with environmental concerns remains a key consideration in expanding oil palm cultivation in Mizoram (Sati, 2023). Enhancement of local livelihoods, promoting landscape heterogeneity as well as biological diversity should be accompanied with tropical forest restoration (Brancalion & Chazdon, 2017). Reducing Emissions from Deforestation and Degradation (REDD+) can enhance forest carbon stocks and provide benefits for biodiversity conservation, forest regeneration along with employment opportunities for the local communities (Edwards et al., 2010).

1.3. Carbon dynamics and net ecosystem productivity

Tree plantations are critical components for resources such as carbon. Forests grow and remove carbon from the atmosphere by storing in the wood, leaves and soil of the trees. In forest ecosystems, carbon is stored in aboveground biomass, belowground biomass and soil and aboveground biomass is a valuable carbon pool (Wang et al., 2024a), especially the trees with their trunk, branches, foliage and roots (Justine et al., 2015). The main carbon pools in a tree based system are the biomass of the living trees with their dead parts, understory, litter and woody debris as well as soil organic matter. Carbon storage in different pools has also been affected by land use change and its rate of changes varies by climatic responses, vegetative cover, choice of species, management practices and anthropogenic disturbances (Thangjam et al., 2022). Soil organic carbon is an important indicator of soil quality as it influences the fertility and productivity by enhancing physical, chemical and biological properties of the soil (Kirschbaum, 2000). It also has a significant role in prediction and mitigation of climate change. SOC can be classified into labile (active) and non-labile (passive) pools based on their residence time. The labile pool is sensitive to environmental changes and is quickly decomposed, while the non-labile pool is more stable and decomposes slowly (Sahoo et al., 2019).

The carbon in biomass of trees will remain in the ecosystem of the forest although they are released back into the atmosphere due to man-made or natural forest fires (FAO, 2006). Live biomass of trees and soil are good carbon sink as they store large amount of carbon (Wang et al., 2024a). Atmospheric carbon dioxide is absorbed by forests through photosynthesis and ultimately contributes to the soil organic pool via decomposition (Nayak et al., 2022).

The balance between carbon sequestration and emission is influenced by various factors such as water content of the soil, plant types, soil characteristics, and microbial activity (Zhongliang, 2011). Natural conditions and human management practices, such as irrigation, fertilization, and agricultural mechanization, significantly impact carbon dynamics in arable lands (Liu et al., 2022; Li et al., 2023). Soil microbes play a crucial role in both the creation and degradation of soil organic matter (SOM) and forming soil organic carbo (SOC), which is a significant source of carbon stock (Kirchman, 2024). Understanding the dynamics of carbon sinks and sources on land has several practical implications, particularly in the context of climate change and environmental management.

Ecosystems are dynamic entities where biomass production and carbon fluxes play crucial roles in sustaining ecological balance. Biomass and productivity are key parameters for understanding the structure and functioning of ecosystems. The productivity of an ecosystem is often regulated by the availability of nutrients in the soil, which serve as fundamental ecological drivers influencing environmental efficiency, global stability, biodiversity, water resources, and the growth medium for plants (Morgado et al., 2018a). A higher nutrient supply can also enhance microbial activity within soil layers, and this microbial enrichment promotes soil respiration, which has recently been identified as a critical flux in ecosystem productivity studies.

In this context, the production, decay, and recycling of plant litter serve as essential components of ecosystem carbon cycling. Litter production represents the transfer of biomass from vegetation to the soil, while litter decomposition and associated respiration release stored carbon into the atmosphere (Giweta, 2020). Together, these processes significantly influence the ecosystem carbon budget and overall productivity.

Ecosystem dynamics and global carbon budgets are assessed generally through gross primary productivity (GPP), this is the total photosynthesis or terrestrial net primary productivity (NPP) (Pathak et al., 2018). Buchmann & Schulze (1999) stated that the NPP represents the stand level (vegetation only) carbon budget and the NEP represents the ecosystem level budget including soil. It is also important to understand the relation between soil nutrient dynamics and net ecosystem productivity of different land use systems. The carbon balance of terrestrial ecosystems can be represented by net ecosystem productivity (NEP) and net ecosystem carbon exchange (NEE). NEP shows the difference between the rate of production of living organic matter (NPP) and the heterotrophic respiration rate of dead organic matter (Ahlström et al., 2015). It quantifies both the accumulation and loss of carbon since it represents the annual change in carbon stored in the ecosystem.

NEP is the difference between the gross primary productivity (GPP) and heterotrophic respiration (RH). Gross primary productivity (GPP) is the total amount of organic matter that plants produce through photosynthesis in a given period of time and it represents the total energy captured by plants from sunlight (Huang et al., 2023). It plays a crucial role in ecological studies and helps in understanding the energy flow through the ecosystems.

In context of research work, GPP is a key parameter used to study the overall assessment of productivity of ecosystems, impact of environmental factors on plant growth and contribution of different plant species to the energy budget of the ecosystem (Yang et al., 2021). It is important in understanding the ecosystem dynamics, carbon cycling and potential effects of climate change in vegetation productivity. The balance between GPP and RH can determine the net ecosystem exchange (NEE) and it can ascertain whether it will be a carbon source (positive) or a sink (negative). It is an essential metric in understanding the carbon cycle and the role of ecosystems in sequestering or releasing carbon dioxide (Kumar et al., 2021). It is frequently expressed in terms of carbon and takes into account both the primary production by plants and carbon loss through plant respiration. Research on NEP is used to assess the carbon dynamics of various ecosystems like forests, grasslands, wetlands and even oceans. Understanding and monitoring NEP is crucial for studying the impact of climate change, land-use changes and other factors on the overall carbon balance of different ecosystems (Arneth et al., 1998; He et al., 2012; Yang et al., 2021).

1.4. Research gap

While numerous studies have focused on biomass production and carbon fluxes, there remains limited attention on developing a holistic understanding of litter production, its decay, and the resulting respiration. This gap is critical, as these processes play a fundamental role in driving ecosystem dynamics and regulating the ecosystem carbon budget. Understanding the interplay between litter production, decomposition, and soil respiration is essential for refining models of ecosystem productivity and carbon cycling (Giweta, 2020). Research on NEP and carbon dynamics reveals significant gaps, particularly in understanding the variability and drivers of these processes across different ecosystems. Current studies have indicated that NEP is influenced by factors such as climate change, drought, and land management practices (Chambers et al., 2001; Beringer et al., 2007; Cao et al., 2023; Huang et al., 2024), yet comprehensive assessments remain limited. Net Ecosystem Production shows significant temporal and spatial variability, particularly under climate change scenarios, with projections suggesting declines in regions such as the Amazon (Huang et al., 2024). In Northwest China, NEP dynamics differ notably across climatic zones, with drought affecting the carbon sink capacity of forests and grasslands in distinct ways (Cao et al., 2023). Accurate carbon dynamics modeling requires a deep understanding of the interplay between NEP and respiration; however, this relationship is frequently underrepresented in current models (Linscheid et al., 2023). The impact of traditional land management practices, such as fire management in grasslands, on NEP and carbon dynamics is underexplored (Pathak et al., 2018). Despite these insights, there remains a pressing need for more integrated studies that address these gaps, particularly in diverse ecosystems and under varying climatic conditions. This could enhance our understanding of carbon dynamics and inform better management strategies.

Plantations are a source of income for many families as they gradually move away from shifting cultivation. The state government has even developed several interventions that will reduce the reliance on shifting cultivations. However, there has been a lack of study on the plantations adopted for such interventions. Mandal & Shankar Raman (2016) found that the bird composition was lower in monoculture plantation such as oil palm and teak when it was compared to jhum lands. Monoculture plantations, while providing employment and potential income, often lead to adverse socio-ecological impacts that affect livelihoods. The transition from subsistence farming to commercial plantations, such as rubber, can lead to agrobiodiversity loss and increased livelihood vulnerability (Fu et al., 2010). The expansion of oil palm plantations has been linked to both job creation and the exploitation of workers. In regions where the shift from agroforests to monoculture has resulted in biodiversity loss and increased poverty among farmers, (Nugraha et al., 2024). Similarly, in rubber-dominated areas, smallholder farmers face income challenges due to price fluctuations, prompting them to adopt diversified income-generating activities (Wang et al., 2023). Furthermore, while forest plantations can enhance soil carbon sequestration, they also disrupt traditional livelihoods, leading to conflicts over land use (Poultouchidou, 2012). Overall, monoculture expansion often undermines smallholder food security and community stability. Therefore, land use policies and conservation plans should be thoroughly researched prior to implementation, while promoting improved practices, such as integrating forest remnants, native trees, and riparian vegetation into monoculture plantations.

1.4.1. Scope of the study

Monoculture plantations have significant impacts on soil carbon sequestration and farmers' livelihoods. While forest plantations can increase soil organic carbon compared to farmland (Poultouchidou, 2012), they often reduce biodiversity and key livelihood tree species richness. However, small-scale rubber plantations can enhance livelihoods when supported by strong institutions and proper management practices (Nath et al., 2013). To mitigate risks associated with monoculture plantations, mixed cropping and agroforestry systems are recommended (Fu et al., 2010; Nath et al., 2013). The impact of plantations on local communities varies, with those living closer to plantations experiencing both benefits (e.g., firewood access, job opportunities) and challenges (e.g., land loss, wildlife conflicts) (Poultouchidou, 2012). Balancing economic gains with sustainable resource use and biodiversity conservation remains a key challenge in plantation-dominated landscapes. Despite these challenges, monoculture can lead to increased efficiency in production and economic growth, potentially benefiting certain sectors of the economy. However, it is crucial to look at the long-term socio-ecological costs associated with such practices.

RESEARCH OBJECTIVES:

Objective 1: To estimate biomass and carbon stocks in different pools of selected plantation.

Assessing the potential of different plantations in their carbon inventories could contribute to their future adoption. For this we selected four major plantations in Mizoram viz., rubber, oil palm, areca nut and teak plantation. These plantations are of same aged (15 years old), fully developed, well-structured and are uniformly maintained. We assumed that each plantation will have different carbon stock which have reached a point of more or less stability, meaning there won‘t be much change as they have reached a level of maturity. Carbon sequestration rate of each plantation will provide valuable information on plantation that can store large amount of carbon and which might not have high carbon sequester potential. The rate of carbon accumulation will vary depending on factors like vegetation type, soil conditions, and land-use history.

In order to meet this objective, the following studies were carried out:

i. Find suitable allometric equations, preferably suitable for north-east India and age-appropriate with the plantations,

ii. Evaluate above and belowground biomass of carbon, leaf fall and carbon input of different plantations,
iii. Evaluate the carbon stock from the initial time and after a certain number of periods was taken,
iv. Assess the difference between the initial and the final time period will give us the rate of carbon sequestration and,
v. The carbon dioxide equivalent was also evaluated.

Objective 2: To assess the soil properties and soil carbon storage of the selected plantations.

The soil properties and soil carbon storage of each plantation will provide valuable information on plantation that can store large amount of carbon and which might not have high carbon sequester potential. The rate of carbon accumulation will vary depending on factors like vegetation type, soil conditions, and land-use history.

To assess the assumptions, the following data obtained from the fields were evaluated by following the methods as entitled below:

i. Evaluate the SOC concentration and SOC stock in the different plantations,
ii. Evaluate the soil properties in each plantation,
iii. Assess the relationship between soil parameters and carbon fractions in the soil and
iv. Assess the active and passive carbon pools of each plantation

Objective 3: To estimate net ecosystem production and carbon dynamics in selected plantations.

The organic carbon content of the soil under different land uses are affected by the rate of organic input from above and belowground litters. Dead leaf is aboveground litter and dead fine roots are belowground litter, their productions and decay rates are crucial for each plantation. Study of fine root dynamics under each plantation is also imperative for net ecosystem productivity research. Since forest floor are rich with dead matters, belowground litter production quantification by quantifying the dead roots is crucial for this study.

To test the assumptions, the investigation was done on the following major objectives:

i. Evaluate the aboveground and belowground litter through their litter production and decay,
ii. Evaluate the aboveground and belowground mortality through the dead biomass and litter,
iii. Evaluate the NPP for both aboveground and belowground from their live biomass and mortality,
iv. Evaluate soil respiration through Qubit in each plantation,
v. Evaluate SOC at different depths for each plantation, and,
vi. Asses the NEP for each plantation.

CHAPTER II- REVIEW OF LITERATURE

2.1. Climate change and land-use change

Rising greenhouse gas emissions have driven significant and rapid transformations across the atmosphere, oceans, cryosphere, and biosphere. The global surface temperatures during 2011-2020 averaged 1.1°C higher than the pre-industrial period (1850-1900). Human-induced climate change nevertheless is intensifying weather and climate extremes worldwide, causing widespread harm to ecosystems, economies, and societies. These impacts disproportionately affect vulnerable communities—those that have historically contributed the least to global emissions. Additionally, human activities now pose an unprecedented threat to biodiversity, increasing the risk of species extinctions on a global scale (IPCC, 2021). Deforestation, particularly in tropical regions, raises local temperatures and alters rainfall patterns, exacerbating the impacts of global climate change and posing serious risks to agricultural productivity (FAO, 2024).

The changes in land use are one of the most prominent sources of carbon dioxide by human activities, with particular emphasis on conversion of natural forests to plantation and croplands. These impact the balance between the rate of input and output of soil organic matter as a consequence of changes in plant community and practice in land use management (Sahoo et al., 2019). In the current global environment scenario, one of the prime concern which is responsible for climate change is the increasing levels of greenhouse gases (GHGs) concentration- mainly carbon dioxide (CO_2) in the earth‘s atmosphere. In the tropical ecosystems, carbon storage has been disrupted due to land use change by releasing GHGs (carbon emissions) at 10%-13% annually (Shiraishi et al., 2023). The reduction in emissions along with the removal of GHGs from the atmosphere is crucial in moderating the rise of the global average temperature below 2°C; this is above the pre-industrial levels of the Paris Agreement (Fuss et al., 2014). Land use changes, especially the conversion of natural forests to agricultural land, have been found to significantly impact soil organic carbon (SOC) pools. Research suggests that cultivated soils may lose 21-36% of their total organic carbon compared to uncultivated soils, with even greater losses reported across different agro-climatic regions in India (Sahoo et al., 2018; Singh et al., 2023). The terrestrial ecosystem continue to absorb anthropogenic CO_2 through carbon dioxide fertilization, offering an opportunity to prioritize land management practices that promote plant growth and carbon sequestration. Strategies such as reforestation and sustainable agriculture should be emphasized in climate action plans to maximize carbon uptake (Kirchman, 2024).

The Kyoto Protocol provides a framework for addressing land-use, land-use change, and forestry (LULUCF) activities, which are crucial for carbon sequestration and emission reduction, particularly in developing countries like India. While the protocol did not explicitly mention LULUCF, it allows for the inclusion of these activities, presenting both opportunities and challenges for countries seeking to implement carbon credit projects (Bloomfield et al., 2000). India, with its diverse ecosystems, has significant potential for soil carbon sequestration, although there are obstacles such as establishing credible baselines, ensuring additionality, and managing the complexities of soil carbon dynamics (García-Oliva & Masera, 2004). The evolving accounting rules and methodologies for LULUCF under the Kyoto Protocol, including the use of remote sensing for verification, are essential for enhancing transparency and effectiveness in carbon accounting (Fry, 2007). Thus, India's involvement with LULUCF under the Kyoto framework is pivotal for its sustainable development and climate change mitigation efforts.

The Kyoto Protocol has significantly influenced India's approach to climate change through mechanisms like the Clean Development Mechanism (CDM), which allows developing countries to participate in emission reduction efforts. Despite India's active involvement in the CDM during the first commitment period (2008-2012), studies indicate a persistent increase in carbon dioxide emissions, driven by economic growth, energy consumption, and trade openness, suggesting a lack of commitment to curtail emissions (Gupta, 2014; Bhat & Mishra, 2018).

As of 2020, global forest cover stood at approximately 4.1 billion hectares, accounting for 30% of the Earth's land area (FAO & UNECE, 2021). India accounts for two-thirds of this global forest area. Between 1990 and 2002, about 420 million hectares of forest were converted to other land uses. The rate of forest loss declined from 15.8 million hectares per year during 1990–2002 to 10.2 million hectares per year between 2015 and 2022 (IPCC, 2021).

Forests also serve as vital habitats for much of the planet's terrestrial biodiversity, which supports local livelihoods and strengthens the resilience of agri-food systems. The area and growing stock of naturally regenerated temperate and boreal forests are projected to expand, indicating potential growth in timber production, though uncertainties remain (FAO & UNECE, 2021). Some projections suggest that forest plantations could increase by 20–40 million hectares by 2050 to help meet rising wood demand (Nepal et al., 2019). However, the productivity of these plantations will depend on various factors, including their age, climate conditions, the species planted, and the management practices employed.

2.2. Plantation-based livelihood in Mizoram

In Mizoram, livelihood still heavily relies on agriculture, particularly shifting cultivation (jhum), although it faces challenges due to natural hazards, inadequate infrastructure, and limited financial and physical capital for sustainable plantation practices (Sati & Vangchhia, 2017b). Mizoram primarily relies on farming and forest products with plantation agriculture having a significant aspect; however, many natural resources are still unused, hindering the economic development (Sati & Vangchhia, 2017a). The increase in population has led to a critical reduction in the jhuming cycle which resulted in decreased land productivity. This has caused detrimental effects on the environment, emphasising the demand for sustainable agricultural practices. The state government launched policies such as New Land Use Policy (NLUP) in 1984 that had been implemented to provide alternative livelihoods to families engaged in shifting cultivation through various trades and occupations but had not significantly improved economic conditions or reduced jhuming practices (Garbyal, 1999).

Teak plantations in Mizoram have an important role in local agroforestry system and carbon sequestration efforts. The intercropping of *Oryza sativa* L. (paddy) with *Tectona grandis* Linn.f. (teak) has demonstrated both economic viability and ecological to mitigate the adverse effects of shifting cultivation in the region (Lalramnghinglova & Jha, 1996). Studies have shown that teak plantations can store substantial amount of carbon with the total carbon stocks increasing with the age of the plantation and can reach up to 732 Mg ha^{-1} in older teak stands (Jha, 2015). Moreover, the growing stock in various teak forests stands in Mizoram showed considerable variation, their densities ranging from280 to 620 stems per hectare and total growing stocks between 284.7 and 669.01 m^3 ha^{-1} (Khanduri et al., 2008). Teak plantations also demonstrate high soil organic carbon (SOC) stocks, with 39.03±5.3 Mg C ha^{-1}, indicating good soil fertility and productivity. Thus, teak plantations in Mizoram play a crucial role in promoting ecological sustainability and supporting the region‘s economic stability (Sahoo et al., 2023; Hrahsel & Sahoo, 2024).

Several north-eastern states in India, including Mizoram, have been seen as a potentially suitable area for rubber plantation due to its favourable agro-climatic conditions. Rubber plantations in Mizoram can enhance livelihoods by utilizing 29.08% of the geographical area for cultivation, leveraging favourable conditions for economic production (Lallianthanga et al., 2014). Oil palm plantation in Mizoram was revived around 2004 with the passing of ―The Mizoram Oil Palm Act, 2004‖ by the state‘s legislative assembly. It expedites partnerships with big companies like Godrej Agrovet Ltd. and Ruchi Soya Industries Ltd. to promote oil palm farming among local farmers. The state government actively encouraged farmers to transition from traditional crops to oil palm, aiming for better economic growth and higher incomes. To support this shift, the government provided subsidies, free nursery plants, and financial assistance during the crop‘s gestation period. However, despite these efforts, only 20% of farmers were reported to be satisfied with the oil palm plantation (Lalawmpuia et al., 2020). Key challenges include inadequate infrastructure for transportation of harvested fruits and the labour-intensive nature of harvesting. As a result, this created a shift to in focus from oil palm to areca nut, which was seen as more economically viable.

Areca nut (*Areca catechu* L.) cultivation in Mizoram presents both opportunities and challenges, particularly in enhancing productivity and sustainability. Adopting a cropping systems approach, which includes intercropping with shade-tolerant species like turmeric, cocoa, and black pepper, can enhance resource use efficiency and profitability (Sujatha et al., 2016).

Sahoo et al. (2023) investigated numerous plantation systems including secondary forests, oil palm, orange and areca nut plantations that were established on degraded shifting cultivation lands and found that plantations such as oil palm, orange and areca nut in Mizoram can be linked to a source of livelihood. However, secondary forests were seen to have better soil organic storage as well as sustainability under climate change scenarios. There were also concern amongst the plantation farmers regarding soil erosion and decline in diversity of species especially primate and birds (Lalawmpuia et al., 2020). Also, areca nut plantation in Mizoram has the lowest soil organic carbon stock compared to other plantations studied (Hrahsel et al., 2018).

2.3. Carbon pools in the ecosystem

Tropical forests play a crucial role in global carbon storage, holding approximately 40% of the Earth's terrestrial biomass carbon (Karmakar et al., 2020). They also contribute significantly to photosynthesis, a process vital for sustaining ecological balance. The five major carbon pools in terrestrial ecosystem are belowground biomass (BGB), aboveground biomass (AGB), litter, soil organic carbon (SOC) and deadwood (IPCC, 2006). Carbon storage and biomass plays an important factor in the global carbon cycle (Houghton, 2005), especially the biomass of tree (Fahey et al., 2010). Majority of the total carbon is stored in the aboveground biomass such as the trunk, branches and foliage (Sharma et al., 2010; Aholoukpè et al., 2013; Du et al., 2015; Nath et al., 2019). The largest source of carbon storage after establishment of plantation is the tree as they serve as a reservoir for carbon (Aholoukpè et al., 2013). The main stem wood sequesters carbon longer, while other parts sequester and liberate carbon on rapid intervals due to pruning and decomposition (Sharma et al., 2010). Numerous studies have emphasized the significance of tree diameter in carbon storage, with larger diameters leading to a greater basal area (BA) and, consequently, higher above-ground biomass (AGB) storage capacity (Baishya & Upadhaya, 2014). However, other research also highlights the carbon storage potential of small and medium-sized trees (Borah et al., 2013; Raha et al., 2020), challenging the exclusive focus on larger trees. Although carbon storage of each component tends to increase with age, the proportion of carbon stored in leaves, branches, and roots relative to that in total tree biomass decreased with age (Du et al., 2015). Carbon sequestration potential varies with the tree species, climate, soil and management (Sreejesh et al., 2013). Mature plantations behave as reservoir while younger plantations sequester abundant amount of carbon (Sreejesh et al., 2013).

Stand age is a strong indicator of ecosystem structure and function in plantation forests and may influence carbon storage within the ecosystem (Justine et al., 2015). As stands age, competition for light and nutrients intensifies, potentially affecting the distribution of understory carbon stock. Significant variation in total carbon stock across stands of different ages and species has been observed (Kumar et al., 2023). Stand age plays a critical role in determining overall ecosystem carbon storage and provides valuable insights into carbon sequestration potential (Li et al., 2023).

Carbon sequestration within the framework of the Kyoto Protocol, serves as a significant incentive for addressing land degradation and desertification. This is particularly relevant for countries facing severe land degradation, as it provides a financial mechanism to support restoration efforts (Arnalds, 2002). It is important for there to be community involvement in carbon sequestration projects. Engaging local communities not only enhances the effectiveness of these projects but also addresses the multidimensional consequences of land degradation, such as reduced agricultural productivity and loss of biodiversity. Carbon sequestration can be a powerful tool for combating land degradation and desertification, particularly through financial incentives, community involvement, and targeted projects.

2.4. Relationship between net ecosystem productivity and carbon dynamics

The current understanding of carbon cycles in forest soils and the regulation of heterotrophic respiration is incomplete. As a result, assessments of total forest carbon cycles based solely on growth measurements are limited. Traditional methods of measuring forest growth, such as annual stem volume increment or aboveground biomass increase, often overlook carbon allocated to root turnover (Arneth et al., 1998). This limitation hampers a comprehensive understanding of carbon cycles in forest ecosystems.

Factors that alter over seasons were observed to be a substantial determinant of the net ecosystem efficiency although seasons play less importance in the pine plantations as critical amounts of carbon were incorporated even outside if the active season. This shows a significant leverage of evergreen forests in warm and temperate climates (Novick et al., 2015). The seasonal partitioning of carbon was found to be useful in understanding the complex dynamics and magnitude of carbon allocation in forests among the major European climatic zones (Babst et al., 2014). Biometric measurement and the seasonal net ecosystem productivity (NEP) were proved to be compatible (Babst et al., 2014). Many advances in different techniques of remote sensing can assist in accurate estimation of biometric parameters (Quiñones et al., 2013).

Recently, scientific communities have shown an increased interest in regulatory function of tropical soil since it is a crucial part of biosphere and has a larger potential to store carbon when compared to vegetation and atmosphere (Moinet et al., 2023; Morgado et al., 2018b). The nutrient cycling is a vital function of any ecosystem. Nye (1961) estimated the rate of turnover of organic matter and nutrients in the moist tropical forest. The estimation of biomass and carbon stock of different land use sectors have been reported by many workers. For example, Brown, (1997) estimated biomass carbon of forest ecosystem in global scale. Singh & Sahoo, (2018) estimated biomass and carbon stocks in major land use sectors of Mizoram. Nath et al., (2019) revealed an allometric equation to estimate the tree biomass and carbon of different land-use practices in northeast India. According to IPCC various carbon pools haven been identified within the forest ecosystem and other land use systems (Sharma et al., 1995; Dadhwal et al., 2009). These include soil pool, live vegetation pool, underground root and dead litter pool .

The work done on the productivity of forest ecosystem has been revised by O'Neill et al. (1981). Global productivity pattern in the biosphere have also been estimated by Whittaker & Likens (1975) In India, forest productivity has been studied by Karmacharya & Singh (1992), Singh et al. (2011) and He et al. (2012) as well as many others. Sensitivity of landscape-level NEP changes in disturbance regime varies among the forest types. Increasing harvest removals could hasten recovery of NEP during the first 30 years after clear-cutting, but would be reduced at the end of 80-year harvest of Douglas-fir-forest species as reported by Grant et al (2010). In general productions were found more in the tropical forest than the temperate forest (Westlake, 1963) . Information about the process of nutrient dynamic, NEP and soil respiration rates of different land use systems are still lacking in this part of northeast India.

The persistent applications of organic fertilisers to agro-ecosystems can furthermore cause accumulation of organic carbon in the soil this in turn, will have a big potential for carbon sequestration (Wu et al., 2012). Soil organic pool (SOC) is a very complex & dynamic pool; a steady rise in yield of forest biomass does not necessarily result in increased soil organic carbon stock of the plantation or forest. Soil disturbance due to clear-cut harvesting or preparation of site during the early stages of development will influence the loss of SOC. Some studies have reported no significant increase in mineral soil carbon content with stand age while others showed increasing soil carbon content in the early decades after afforestation. According to a study in southern China (Du et al., 2015), the soil carbon increased in the early stages after afforestation and then decreased gradually with plantation age. This inconsistency may result from differences in forest type, tree species, soil properties, litter quantity and quality, forest management, and climate, all of which influence the effects of forest age on soil carbon storage. Different cropping systems of the plantation will have a significant impact on the soil carbon properties which was observed to be true in the area nut plantations observed in Karnataka (Apurva et al., 2018). The growth of weeds along with fewer disturbances of the soil and the shade of the trees, the accumulation of SOC found to be more in areca nut plantations as compared to paddy and maize land-use cover.

A well-designed and multi-functioning plantation can help in reduction of pressure on the natural forests and restore ecological services that are provided by natural forests, thus help in mitigating climate change via direct carbon sequestration (Paquette & Messier, 2010). Even in sustainable plantation, commercial plantations are currently a central topic to aid in mitigation for climate change (Ming et al., 2014). *Areca* nut trees have high carbon sequestering capability and they are important cash crops especially in Western and Eastern Ghats, east and north eastern regions of India. Oil palm plantations also have a large potential for atmospheric carbon dioxide sequestration by reducing the carbon dioxide from the atmosphere and increase its sequestration by enhancing the quality of the soil, air and habitat (Singh, et al., 2018). Large amount of dry matter is produced by oil palm because of its larger surface area, full ground cover for one year which gives large light interception and total dry matter production when compared to other annual crops. Carbon contents in oil palm were observed to be lower in younger leaves while it was higher in older leaves. Oil palm has also been linked to the drainage of tropical peat lands in Malaysia; however, in Mizoram where shifting cultivation is dominant, it was seen as a sustainable future prospect. Furthermore, the high carbon sequestration potential of rubber plantation increases the marketing of natural rubber from synthetic rubber as high carbon sequestration potential of rubber is related to the natural latex production.

Proper management for restoration of carbon through monoculture plantation varies substantially by the genus of tree and plant functional type. Factors such as genus, endemism, and prior land use and plant traits intensely facilitate the carbon accumulation in monoculture plantations (Bukoski, 2021). In northeast India, degraded lands can be restored through rubber plantation and agroforestry since it can enhance ecosystem carbon sequestration and reduce carbon dioxide emission from changes in land use (Brahma, et al., 2018). Plantations in northeast India can store carbon and help in mitigation of climate change (Mishra et al., 2021). Mature rubber plantations contribute to soil rehabilitation by increasing aggregate stability, recalcitrant carbon pool and soil organic carbon stock and minimizing soil degradation (Kurmi et al., 2020). In rubber plantations, extended rotation can lead to higher carbon sequestration (Egbe, 2012) adopting sustainable land management practices can help restore SOC pools and mitigate the adverse effects of land use changes. Practices such as agroforestry and conservation tillage are highlighted as potential solutions (Sahoo et al., 2023).

Forest management practices can play a crucial role in restoring carbon in forests. Afforestation and reforestation of depleted arable soils can increase SOC stocks, while the selection of tree species also affects SOC storage (Sahoo et al., 2023). Additionally, lower-intensity harvests that retain tree residues on site can reduce SOC losses compared to whole-tree harvests (Bukoski, 2021). Stand thinning has no significant effect on SOC stocks but can increase forest resistance to climate extremes (Schindlbacher et al., 2022). Furthermore, promoting tree species diversity can enhance forest resilience and reduce the risk of SOC losses through disturbances (Li et al., 2023). Silvo-pastoral system management can achieve a balance between productivity and carbon stock maintenance, promoting sustainable forest management (Acuña et al., 2023). These findings highlight the importance of implementing appropriate forest management practices to restore and optimize carbon sequestration in forests. In a subtropical coniferous plantation in China, empirical models were developed to estimate NEP by considering factors like photosynthetically active radiation (PAR) and respiration. In a poplar short rotation coppice (SRC) plantation, NEP was calculated using a combination of eddy covariance techniques and component-flux-based approaches. The results indicated a significant net carbon uptake, with NEP values ranging from 96 to 199 g mC/yr during the second growing season (Zenone et al., 2015). In tropical forest plantations in India, the Carnegie-Ames-Stanford Approach (CASA) model was used to estimate net primary productivity (NPP), a precursor to NEP. The study found that precipitation significantly influenced NPP, explaining over 20% of its variation. Seasonal patterns showed maximum productivity during the wet season (Tripathi et al., 2017). In an *Acacia mangium* plantation in Vietnam, aboveground NPP was found to be highly seasonal, with the highest biomass increment during the rainy season. This seasonal dependency underscores the importance of climatic factors in determining NEP (Thang et al., 2019).

The review of literature reveals that although several studies pertaining to carbon capture and carbon sequestration have been done in various forests of India and north-east India, in particular, the net ecosystem exchange (NEE) of carbon during photosynthesis as well as the release of CO_2 through respiration studies are very limited. Further, the scale of variability in NEE, gross primary productivity of respiration (from aboveground autotrophic of soil respirations combining heterotrophic respiration and belowground autotrophic respiration from plant roots) across seasons or after biophysical drivers have not received due attention. Furthermore, there are limited attempt to understand litter productions, its decay and respiration in matured forests, which in turn are essential in advancing and understanding other ecosystem dynamics and ecosystem budget. Therefore, the present study on assessment of net ecosystem production of carbon dynamics in selected tree plantations of Mizoram would provide important indices on carbon sequestration potential of these plantation forests, their carbon source-sink status, and may help in predicting and assessing the long-term carbon balance with or without anthropogenic disturbances in the state of Mizoram. The findings of the study may further aid in developing proper ecological and environmental policies in effectively managing carbon storage in the future.

CHAPTER III- DESCRIPTION OF STUDY SITE

3.1. Introduction

Mizoram, located in northeast India, has Aizawl as its capital. It is a landlocked state, bordered by Tripura, Assam, and Manipur, and shares international boundaries with Myanmar and Bangladesh. The state's geographical area covers 21,081 square kilometres, positioned between longitudes 92°15'E and 93°92'E and latitudes 21°58'N and 24°35'N. The state extends 277 km from north to south and 121 km from east to west. The state's topography is notably varied and rugged compared to other hilly regions in north-eastern India. Mizoram is characterized by a hilly landscape with rugged terrain, with altitudes ranging from 50 m to 2000 m above sea level. The state boasts a high literacy rate and an agrarian economy. While slash-and-burn farming, known as jhum, has been a traditional agricultural practice, it is gradually being replaced by horticulture and bamboo-based industries.

3.2. Climate

Mizoram enjoys a moderate climate, with winter temperatures ranging from 11°C to 21°C and summer temperatures from 20°C to 30°C. Relative humidity during the dry season ranges between 60–70%, while in the monsoon season it reaches around 90%. The southwest monsoon brings significant rainfall, with an average annual precipitation between 2500 mm and 3000 mm, and the state receives an average of 2327.73 mm annually. The heaviest rainfall occurs between May and September. The climate is divided into four seasons: winter (December to February), summer (March to May), monsoon (June to September), and retreating monsoon (October to November).

Based on its altitude and rainfall, Mizoram's forests can be broadly classified into tropical wet-evergreen forests, montane sub-tropical forests, and temperate forests. The total forest cover of the state is approximately 8,266.08 km^2, accounting for around 39% of its total geographical area. According to the Forest Survey of India (2023), the forest cover percentage of the state‘s geographical area is 85.34, which is the highest among other Indian states.

The climatogram detailing the total monthly rainfall and mean monthly minimum and maximum temperature (Figure 3.1) showed that rainfall was lowest in the year 2021 ang highest in 2024. The minimum temperature decrease in the months of December to February during the sampling period and maximum temperature were high during the summer seasons in all the sampling period. The temperature were all high in the months where the rainfall was heavy.

3.3. Soil

Mizoram is characterized by rolling hills, rivers, and lakes, with predominantly clayey loam soils mixed with angular shale fragments of varying sizes. The soil in Aizawl, the capital, is generally loose and sedimentary, with high porosity and permeability, making the city highly vulnerable to erosion and rain-induced landslides, which cause significant damage to property and life annually. The soils in Mizoram range from sandy loam and clayey loam to clay and are generally mature but heavily leached due to the steep terrain and heavy rainfall. As per USDA classification system, Mizoram soils can be distributed into soil orders viz. Inceptisols (36.0%), Entisols (28.0%), Ultisols (26.0%), Alfisols (2.0%) and others (8.0%) (Bhattacharyya et al., 2013)

According to the Soil Survey of India (SSI), Mizoram has six major soil types: red soil, laterite soil, alluvial soil, mountain soil, peat soil, and clay soil. Approximately 70% of the state‘s total area is covered by hilly terrain. This means that most soils found in Mizoram are derived from parent rocks such as granite and gneiss through weathering and erosion processes over time. These soils are porous, have poor water retention capacity, and are deficient in essential nutrients like potash, phosphorus, nitrogen, and humus—partly due to the traditional practice of shifting cultivation. The soil pH tends to be acidic to neutral, a result of excessive leaching. The pH generally ranges from 4.56-6.08 (Lungmuana et al., 2016; Wapongnungsang et al., 2021). Shifting cultivation, widely practiced in Mizoram, negatively impacts soil productivity by increasing soil acidity, reducing surface moisture, and exacerbating erosion and nutrient loss through runoff.

3.4. Study site- plantation area

The current study was conducted in four monoculture plantations—rubber, oil palm, areca nut, and teak—located in Sakawtuichhun (23.76°N, 92.67°E) and PTC Lungverh (23.92°N, 92.60°E) in Aizawl, Mizoram. These plantations are situated in similar physico-climatic conditions. At the time of the field survey, the plantations were 15 years old. Over a three-year period (December 2020 to December 2023), detailed studies were conducted to analyze the biomass and carbon stock in these plantations, aiming to evaluate their carbon sequestration potential. The net ecosystem carbon balance was also assessed in these plantations.

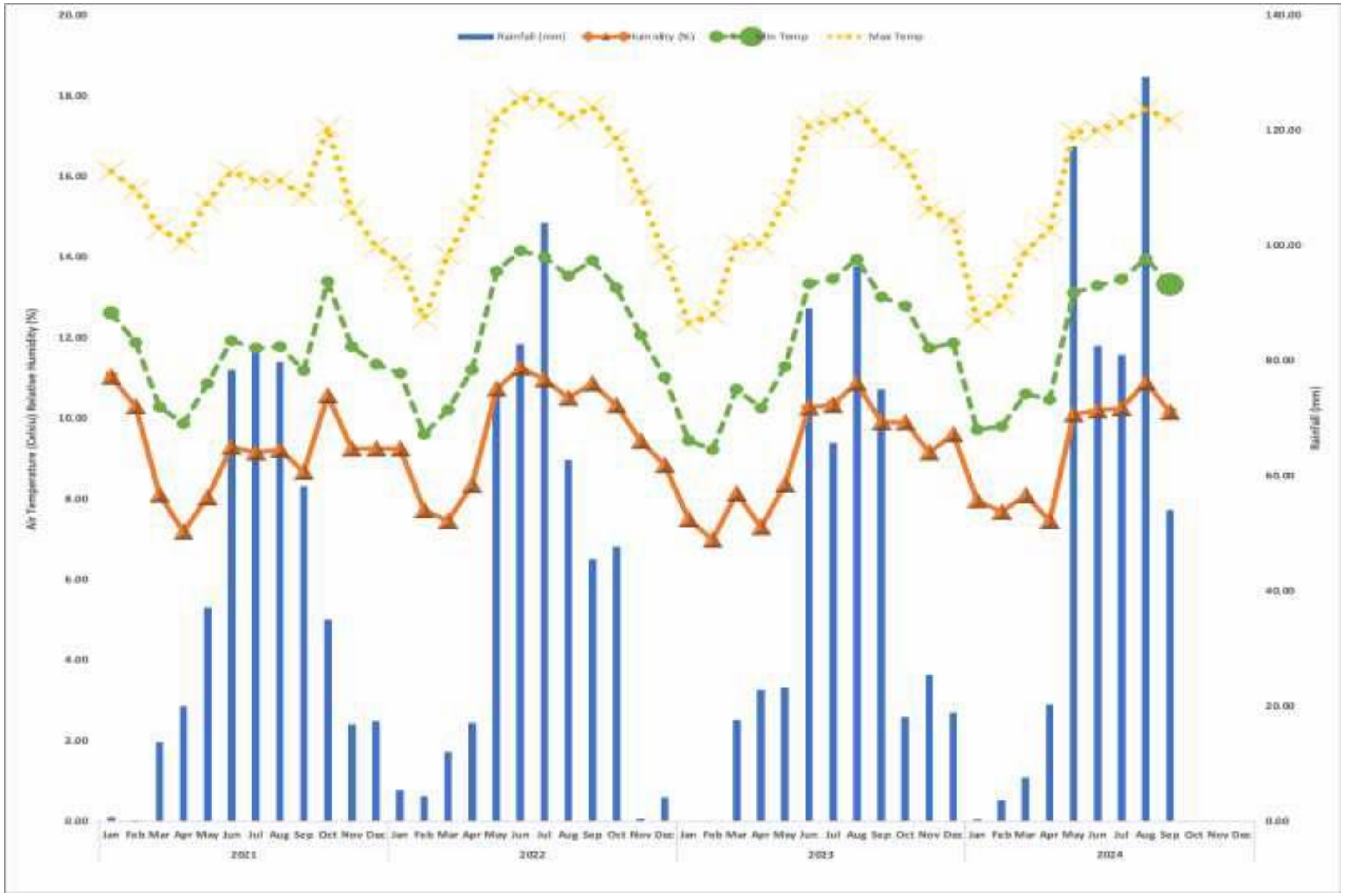


Figure 3.1: Climatogram showing total monthly rainfall and mean monthly minimum and maximum temperatures of Aizawl, Mizoram

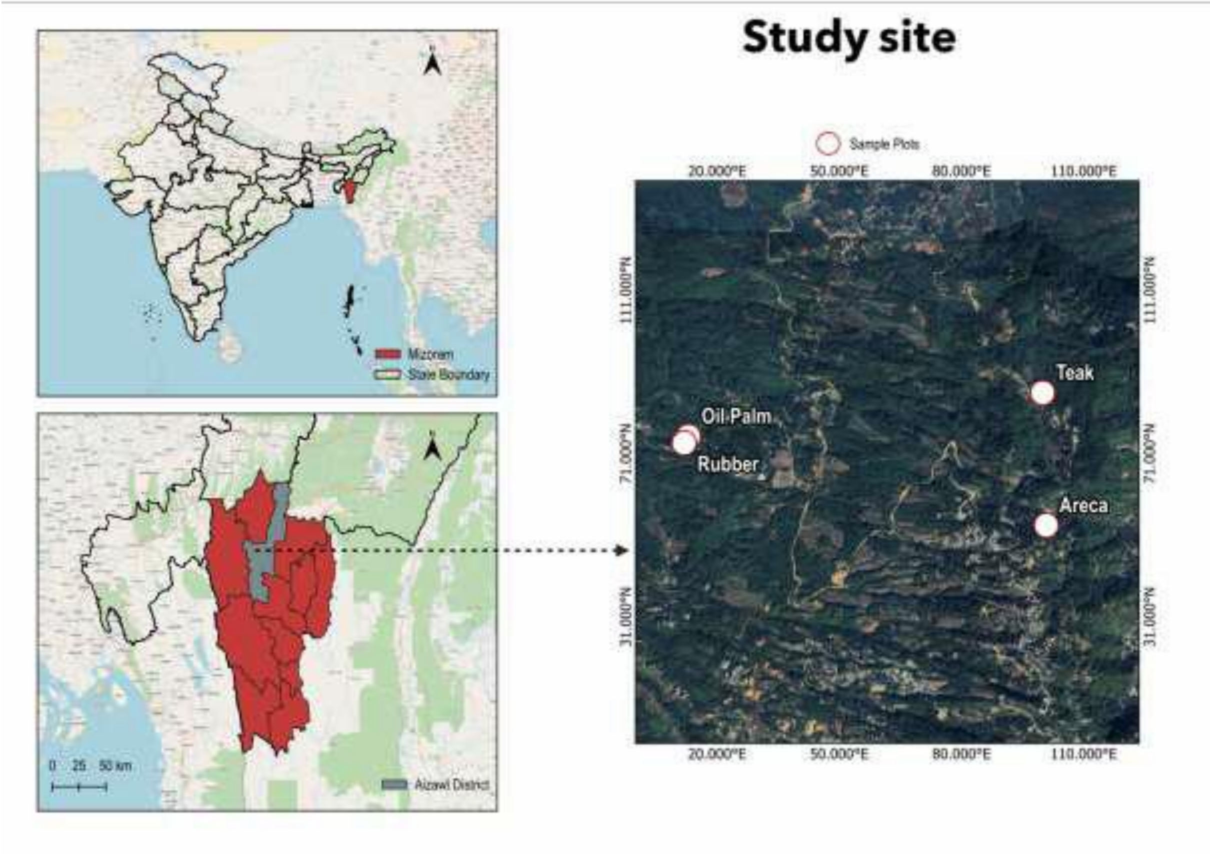


Figure 3.2: Location of study area

Figure 3.3: Plantation selected for the study area

CHAPTER IV- BIOMASS AND CARBON STOCKS IN DIFFERENT CARBON POOLS OF SELECTED PLANTATIONS

4.1. Introduction

Climate change mitigation based on land use gave received tremendous attention on a global scale in the recent years due to its large sink capacity along with economic viability (Bloom et al., 2016). Tropical and subtropical forests are regarded as essential to global terrestrial carbon (C) stocks among terrestrial ecosystems (Bloom et al., 2016; Sullivan et al., 2017). It is well recognized that tropical and sub-tropical regions ate losing forests because of agricultural expansion ad bio-energy production (Hosonuma et al., 2012). The Kyoto Protocol, established under the UNFCCC, advocates for afforestation and reforestation as strategies to enhance wood production and curb greenhouse gas emissions (Oluwadare, 2011). Recognizing carbon sequestration as a key incentive, the Protocol also encourages efforts to restore degraded lands and improve soil conservation (Arnalds, 2002). Additionally, tree plantations offer a range of environmental and socio-economic benefits, such as soil conservation, biodiversity support, renewable energy sources, and employment opportunities (Okorie et al., 2017). Promoting alternative plantation models that engage diverse stakeholders and balance objectives like carbon storage, biodiversity conservation, and rural livelihoods can help maximize their positive impacts.

Biomass represents the total mass of living matter within a specific area, while carbon stocks denote the amount of carbon contained within that biomass. Different ecosystems vary in their capacity to store carbon; for example, coastal macrophyte communities display significant variability in carbon stocks bound to biomass, influenced by habitat type and species characteristics, with hard-bottom habitats generally exhibiting higher carbon storage than soft-bottom areas (Lammerant et al., 2024). Biomass and carbon stocks are crucial for understanding ecosystem functions and their role in climate change mitigation. In forested regions like Mediterranean cork oak forests, advanced technologies such as LiDAR and remote sensing are used to spatially assess biomass and carbon dynamics, revealing long-term trends (Fadil et al., 2024). Additionally, managed landscapes, such as hedgerows, can boost carbon sinks, though management practices greatly influence their carbon storage potential (Black et al., 2023). In secondary forests emerging from former agricultural lands, factors like tree density and age are essential for carbon accumulation, underscoring the importance of land management in restoring carbon stocks (Susanto et al., 2023). Overall, understanding these dynamics is key to developing effective climate change strategies.

Plant biomass plays a crucial role in the global carbon cycle, making its management essential for climate change mitigation (Houghton et al., 2009; Nath et al., 2019). As it grows, biomass can absorb atmospheric carbon dioxide and store it for long periods, thereby contributing significantly to efforts to limit global temperature rise. Forest ecosystems, as significant carbon reservoirs, store substantial amounts of carbon, with studies indicating that aboveground biomass accounts for approximately 53.60% of total forest carbon pools (Wang et al., 2024b). Effective forest management practices, such as thinning, can enhance tree growth and increase carbon sequestration, demonstrating the importance of timely interventions in maximizing carbon stock (Bickovskis et al., 2024). Recent studies have investigated pathways to keep the global temperature increase below 2°C above pre-industrial levels (Griscom et al., 2017; Popp et al., 2017).

Among various carbon pools, vegetation carbon is relatively manageable for reducing atmospheric carbon concentrations, with numerous studies highlighting how sustainable forest management can significantly boost the carbon sink potential of vegetation (Griscom et al., 2017). The global focus on biomass has grown due to its importance as a source of food, energy, and fiber (Houghton et al., 2009). Biomass production in forests depends on multiple factors, including location, species composition (Barbosa et al., 2014; Luo et al., 2014; Li et al., 2015), forest development stages, nutrient availability, and soil properties, alongside natural disturbances, human impact, and management practices (Powell et al., 2014). Thus, over the years, substantial emphasis has been placed on accurately estimating terrestrial biomass, accounting for uncertainties in forest management (Weiskittel et al., 2015).

In many regions, information on the biomass or carbon sequestration potential of plantations remains limited. Carbon stocks in plantations vary significantly across different species, ages, and management practices. Variation in carbon stock greatly influence plantations as some plantations such as rubber (Brahma, et al., 2018) are observed to have vast potential in terrestrial carbon sequestration. Soil organic carbon (SOC) levels also vary with different plantations (Hrahsel & Sahoo, 2024) as the type of plantations affect the levels of SOC present in the soil. Moreover, the age of the plantations has an important role as the older stands tend to increase the carbon stocks in the biomass while decreasing them in the soil systems (He et al., 2021). Thus, the type of plantation has a role in the variation of carbon pools in a monoculture plantation.

Furthermore, biomass represent an emerging carbon pool that can sequester carbon, although this comes with trade-offs related to biodiversity and food security (Kaufmann et al., 2024). Collectively, these insights underscore the multifaceted relationship between biomass, carbon stock, and climate change mitigation efforts. There is potential in these plantations for carbon sequestration, although the understanding of their biomass storage and carbon dynamics is limited. The study of biomass and carbon stock variation is crucial for understanding ecosystem health, mitigating climate change, and informing environmental management strategies.

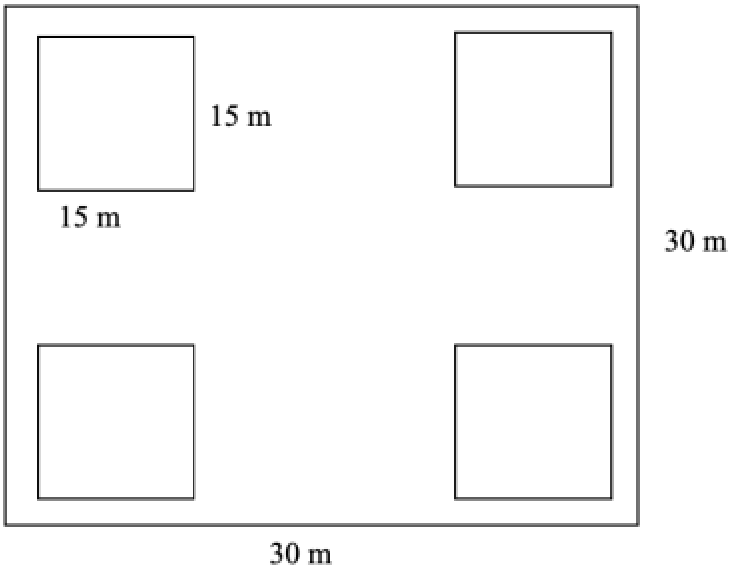
4.2. Methodology

4.2.1. Study area- selected plantations

The study was conducted in the Aizawl district of Mizoram. Four plantations *viz.* rubber (*Hevea brasiliensis* Müll.Arg.), oil palm (*Elaesis guineensis* Jacq.), areca nut (*Areca catechu* L.) and teak (*Tectona grandis* L.f.) in Aizawl district were chosen based on their similar physico-climatic terrain as well as their significant importance in economic, environmental and social contributions. The ages of these plantation were approximately 15 years at the time of field visit. Geographical coordinates of the selected plantations were taken using a mobile based GPS.

4.2.2. Tree Vegetation Sampling

A reconnaissance survey was conducted, during which information about the plantation's history and ages was gathered from the landowners or caretakers. Four quadrats (15 m x 15 m) were placed randomly in the site for sampling of trees. All trees exceeding 30 cm girth over bark at breast height (1.37 m) were identified and tagged. The girth was measured using a metal tape and height was estimated using pole method during December 2020-March 2021 and December 2023-March 2024. Since it was a monoculture plantation with little to no other trees, there were hardly any other trees to be identified.



4.2.3. Aboveground and Belowground Biomass Estimation

A total of 390 individual trees were considered from the four plantations for the aboveground and belowground estimates. The biomass for each plantation was derived from allometric equation that were already developed for the respective tree species with preference being given to those developed for north-eastern India. Shrubs were measured using collar diameter. Herbaceous undergrowth was taken using destructive method from a 1 m x 1 m quadrat at four random sites in each plantation. Litter floor biomass was taken from four random 1m x 1m quadrats, where the fresh and dried weight were recorded.

The following biomass equations were used to estimate the aboveground biomass (AGB)

Sl No	Species	Biomass Equation	References
1	*Hevea brasiliensis* Müll.Arg.	Biomass= $-(\exp(1-3.31+0.95(\ln D^2 H)) \times 1.02$	Brahma, et al., (2018)
2	*Elaesis guineensis* Jacq.	Biomass = $71.797 \times H - 7.0872$	Asari et al., (2013)
3	*Areca catechu* L.	Biomass = $\exp(-1.853+0.728(\ln D^2 H))$	Das et al, (2021)
4	*Tectona grandis* L.f	Biomass = $0.4989D^2-0.202D-21.971$	Jha, (2015)

Belowground biomass component was estimated by the models developed by Cairns et al., (1997):

$$BGB = \exp[-1.0587 + 0.8836 \times \ln(AGB)]$$

Where, BGB and AGB are belowground and aboveground biomass in Mg ha^{-1}.

4.2.4. Biomass Carbon Stock Estimation

Total biomass was calculated by addition of aboveground and belowground biomass. AGB consisted of both biotic and abiotic factors such as trees, shrubs and deadwood. These were converted to carbon by the conversion factor 0.40, where 40% of the dry mass is assumed to be carbon (IPCC, 2007). For standing dead wood, diameter was measured from one end (D1) as DBH or above the root buttress and height was also measured. Diameter at the upper end (D2) was estimated using the taper function (Chambers et al., 2001). Fallen deadwood measured in the field by measuring the length and diameter at both ends (D1 and D2) using a measuring tape.

Wood decomposition class values were estimated where stable decomposition was given 0.69, rotten coarse as 0.34 and rotten fine as 0.41. Herbs and litter components carbon content can be assessed using ash content method (Negi et al., 2003).

4.2.5. Soil Organic Carbon (SOC) and SOC Stock

Soil organic carbon was determined by Walkley & Black (1934) rapid titration method and the SOC stock was determined by considering SOC concentration, bulk density (corrected for coarse fraction) and soil depth using the following equation:

$$\text{SOC stock (Mg ha}^{-1}) = [\text{SOC\%} \times \text{corrected BD (Mg m}^{-3}) \times \text{T (m)} \times 10^4 (\text{m}^2\ \text{ha}^{-1})]/100$$

Where, BD = bulk density (Mg m^{-3})

T = depth of soil (m)

4.2.6. Total Carbon Stock

The total carbon stock is the sum of aboveground biomass and belowground biomass multiplied by 50% carbon content assumed of the entire biomass:

Total Carbon Stock, TCS = (AGB+BGB) × 0.5

4.2.7. Carbon Sequestration Rate

The carbon sequestration rate was calculated by:

$$\frac{\textit{Final Year - Initial Year}}{\textit{Time period between the Initial and final year}}$$

4.2.8. CO^2 Potential

The CO_2 potential was estimated by converting into CO_2 equivalents by which, the carbon stock is multiplied with factor 3.67, which has the value from the ratio of CO_2 to C (44/12 = 3.67)

Carbon stock of trees x 3.67

4.3. Statistical Analysis

Analysis of data was performed using Microsoft Excel 2019 (Version: 16.79.2) and SPSS (IBM SPSS Statistics 25). One-way and two-way ANOVA were performed between the different plantations and soil depth along with the various soil parameters. Test of significance was performed using Tukey's HSD with $p \leq 0.05$, where p value greater than 0.05 were rejected. SPSS was used for estimating Pearson's correlation and analysis of variance.

4.4. Results

4.4.1. *Plantation species diversity and characteristics*

During the survey in 2021, a total of 371 individual trees from four selected plantations were surveyed. A total of 111 rubber trees, 39 oil palm trees, 118 areca nut and 103 number of teak plantations were sampled. In rubber and teak plantation, tree individuals in 50-60 cm were at maximum and 20-30 cm was maximum in areca nut plantation. Due to the different proportion of oil palms, the girth class was relatively larger, and the maximum number of trees was seen in 300-350 cm girth class (Figure 4.2). Proportional distribution of trees in different girth class in the four plantations are presented in Figure 4.1. The height of trees in each plantation exhibited a similar trend with their basal area. The basal area increased with the height of the trees as observed in each plantation as seen in Figure 4.3. There was positive correlation between the height of the trees and their DBH ($p<0.01$) as seen in Table 4.2. However, no signification relationship was observed in oil palm between its height and DBH. As shown in Table 4.1, oil palm had the highest GBH due to its large trunk compared to other plantations, which was followed by teak at 71.68 cm, rubber at 54.32 cm and area nut at 28.42 cm. Teak and rubber plantation have their height at an average of 9.95 m and 9.63 m respectively, while oil palm and areca nut plantations have their average height at 8.54 m and 8.13 m respectively.

The maximum density of rubber and teak trees were observed in 50-60 cm GBH class while the minimum was seen in GBH class >110 cm and 20-30 cm respectively for rubber and teak plantation (Figure 4.4). Areca plantation had the highest density in GBH class 20-30 cm and the lowest density in 40-50 cm GBH class. Oil palm plantation has the highest tree density between 300-350 GBH class followed by 350-400 cm however, the other GBH class have the same tree density. The highest basal area in rubber plantation was seen in 60-70 cm GBH class at 17.58 m^2ha^{-1} and lowest in 10-20 cm GBH class at 0.08 m^2ha^{-1}. In areca plantation, the basal area increased in the order 30-40 cm > 20-30 cm > 40-50 cm > 10-20 cm with the highest value at 66.36 m^2ha^{-1} and the lowest at 7.56 m^2ha^{-1}. The basal area with the highest value was seen in teak at 16.41 m^2ha^{-1} (GBH class >110 cm) and the lowest at 0.09 m^2ha^{-1} (20-30 cm). in oil palm, the highest value was observed to be 2.75 m^2ha^{-1} at 300-350 cm GBH class and the lowest at 0.38 m^2ha^{-1} in 200-250 cm GBH class interval.

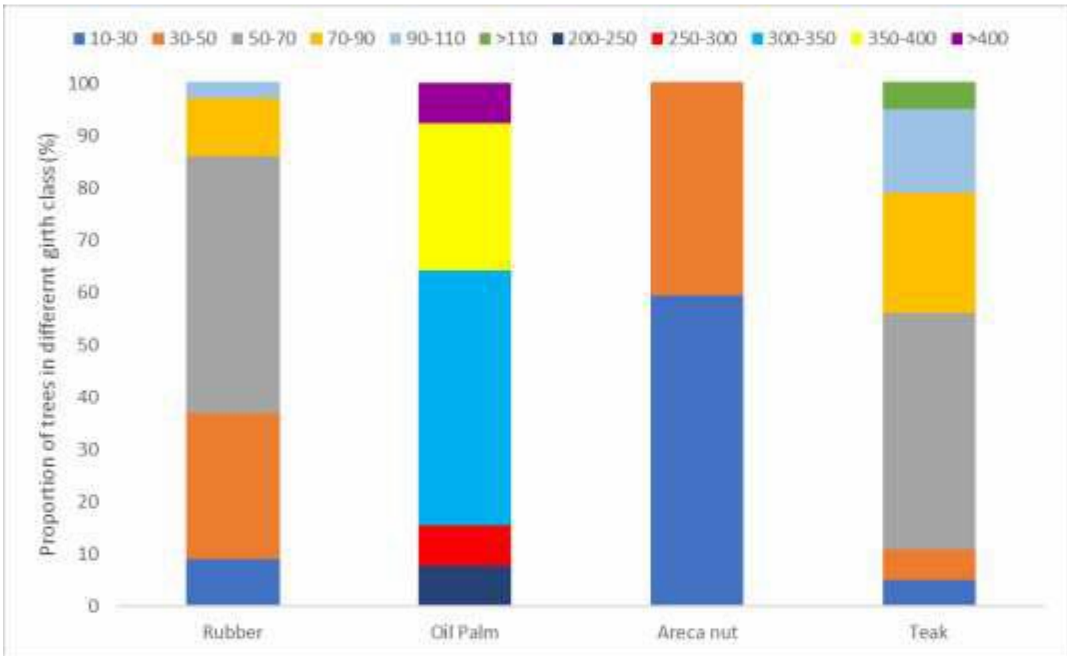


Figure 4.1: Proportion of tree species in different girth class in selected plantations of Aizawl, Mizoram.

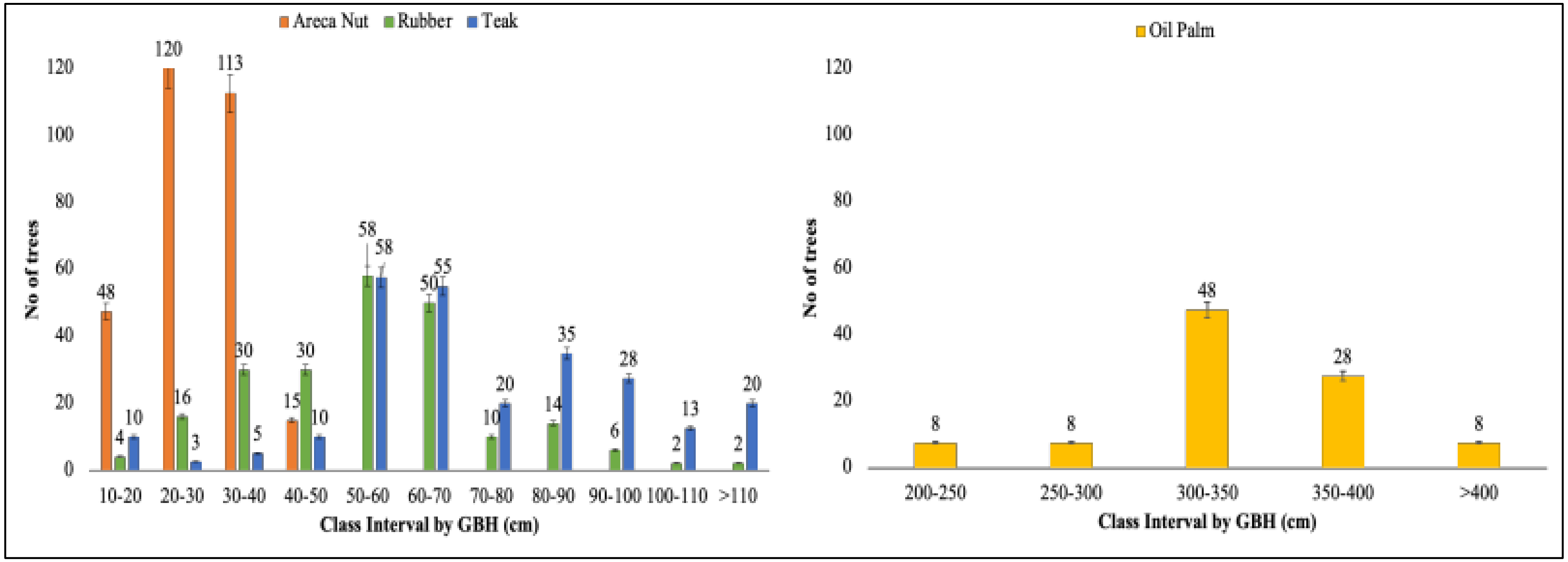


Figure 4.2: Frequency distribution of trees of different girth class in selected plantations of Aizawl, Mizoram

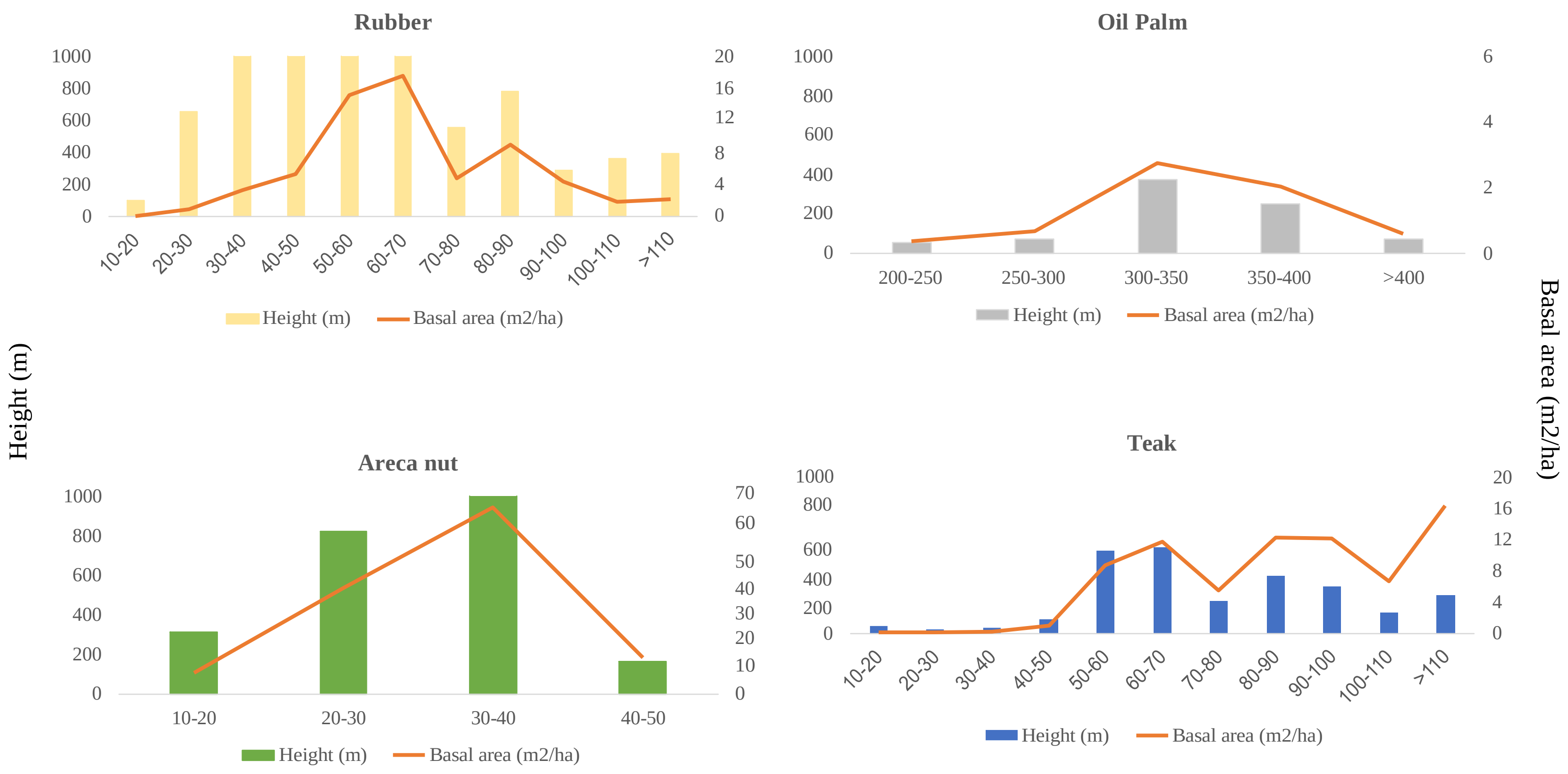


Figure 4.3: Height (m) vs. Basal area (m^2/ha) of selected plantations in Aizawl, Mizoram.

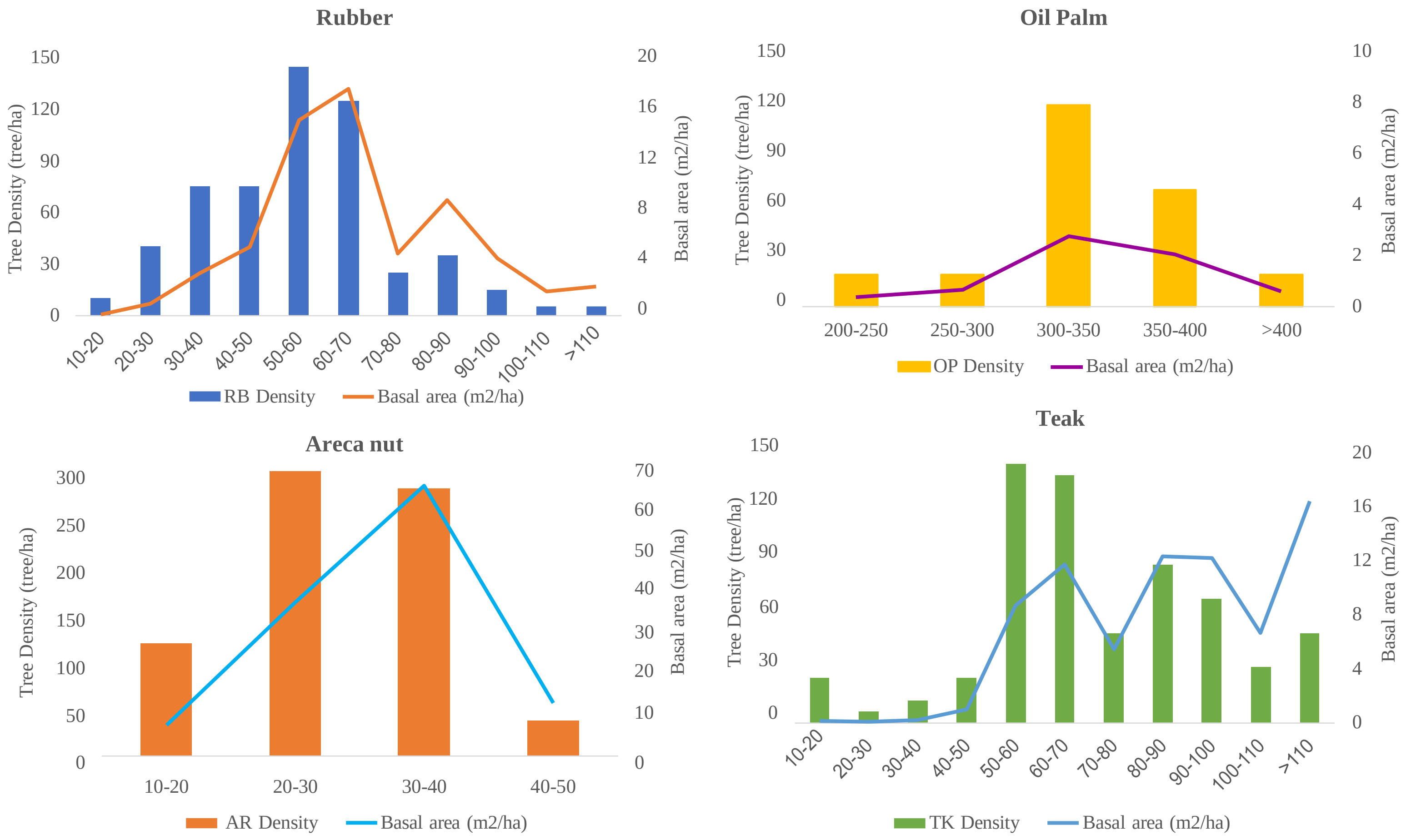


Figure 4.4*:* Contribution of tree stand density and basal area based on the diameter (DBH) class distribution.

Table 4.1: Average GBH, height and basal area of selected plantations in Aizawl, Mizoram.

Parameters	Rubber	Oil palm	Areca nut	Teak
GBH (cm)	54.32 ± 1.76	328.33 ± 7.62	28.42 ± 0.67	71.68 ± 2.64
H (m)	9.63 ± 1.97	8.54 ± 0.28	8.13 ± 0.35	9.95 ± 0.18
Basal Area (m2/ha)	1.16 ± 0.07	17.43 ± 2.59	0.75 ± 0.03	0.75 ± 0.05

Table 4.2: Pearson‘s correlation between GBH and height and basal area of selected plantations in Aizawl, Mizoram.

Parameters	Rubber		Oil Palm		Areca Nut		Teak	
Correlation	**GBH**	**Height**	**GBH**	**Height**	**GBH**	**Height**	**GBH**	**Height**
GBH	1	.377**	1	0.107	1	.413**	1	.644**
Height	.377**	1	0.107	1	.413**	1	.644**	1
**Correlation is significant at the 0.01 level (2-tailed).								

4.4.2. *Biomass of selected plantations*

Rubber plantation had the highest amount of total biomass and biomass carbon as compared to other plantations (Figure 4.5). Based on the analysis of variance, significant interspecific differences were also found between the aboveground biomass and carbon storage. However, there were no significant differences between the four plantations. Besides, the tree biomass and biomass carbon decrease in the following order: Rubber > Teak > Oil palm > Areca nut. The distribution of biomass across major pools in the different plantations are presented in Table 4.3. Higher values of biomass were observed in rubber and teak plantation. The living biomass (aboveground and belowground) values were significantly

($p<0.05$) greater than the non-living biomass. However, there were no significant difference among the different plantations. The belowground biomass was in this order: Rubber > Teak > Oil palm > Areca nut. The non-living biomass was also the highest in rubber plantation followed by oil palm, areca nut and teak.

Rubber plantation was estimated to store 101.36 ± 4.57 Mg ha^{-1} of biomass from trees, which was the highest amongst the selected plantations (Table 4.4.) This was followed by teak plantation (76.963 ± 2.93 Mg ha^{-1}), oil palm plantation (56.844 ± 2.88 Mg ha^{-1}) and areca nut plantation (24.839 ± 1.822 Mg ha^{-1}) plantation. Thus, areca nut plantation had the lowest tree biomass. The post-hoc analysis illustrated significant differences in the biomass of trees between rubber plantation and areca nut plantation ($p=0.007$) as well as between areca nut plantation and teak plantation ($p=0.014$). However, no significant difference was observed between oil palm and the other plantations on their tree biomass.

The shrub biomass was quite low in all the selected plantations compared to the tree biomass. Rubber had the highest biomass value in shrubs (0.429 ± 0.02 Mg ha^{-1}) as compared to other plantations. One-way ANOVA analysis revealed no significant differences between the biomass of the shrubs amongst the different plantations.

Rubber plantation had the highest herb biomass at 0.521 ± 0.02 Mg ha^{-1} followed by oil palm (0.304 ± 0.04 Mg ha^{-1}), teak (0.261 ± 0.01 Mg ha^{-1}) and areca nut (0.253 ± 0.01 Mg ha^{-1}) plantations. One-way ANOVA analysis indicated there was a significant difference at $p<0.05$ between the herb‘s biomass of the selected plantations. Post-hoc analysis indicates a significant difference between oil palm and area nut ($p=0.015$) and between oil palm and teak ($p=0.017$).

Areca nut plantation had the highest litter biomass (1.116 ± 0.30 Mg ha^{-1}) when compared to other plantations selected. It was preceded by oil palm (0.728 ± 0.04 Mg ha^{-1}), rubber (0.620 ± 0.05 Mg ha^{-1}) and teak (0.551 ± 0.03 Mg ha^{-1}). No significant differences were observed in litter biomass.

Oil palm deadwood biomass was the highest (2.351 ± 0.1 Mg ha^{-1}) which was followed by rubber (1.027 ± 0.04 Mg ha^{-1}), areca nut (0.491 ± 0.03 Mg ha^{-1}) and teak (0.272 ± 0.05 Mg ha^{-1}). There was a significant difference ($p<0.005$) between the deadwood of the selected plantations and post-hoc analysis exhibited significant difference between the oil palm plantation and areca nut plantation ($p=0.010$) and teak plantation ($p=0.005$).

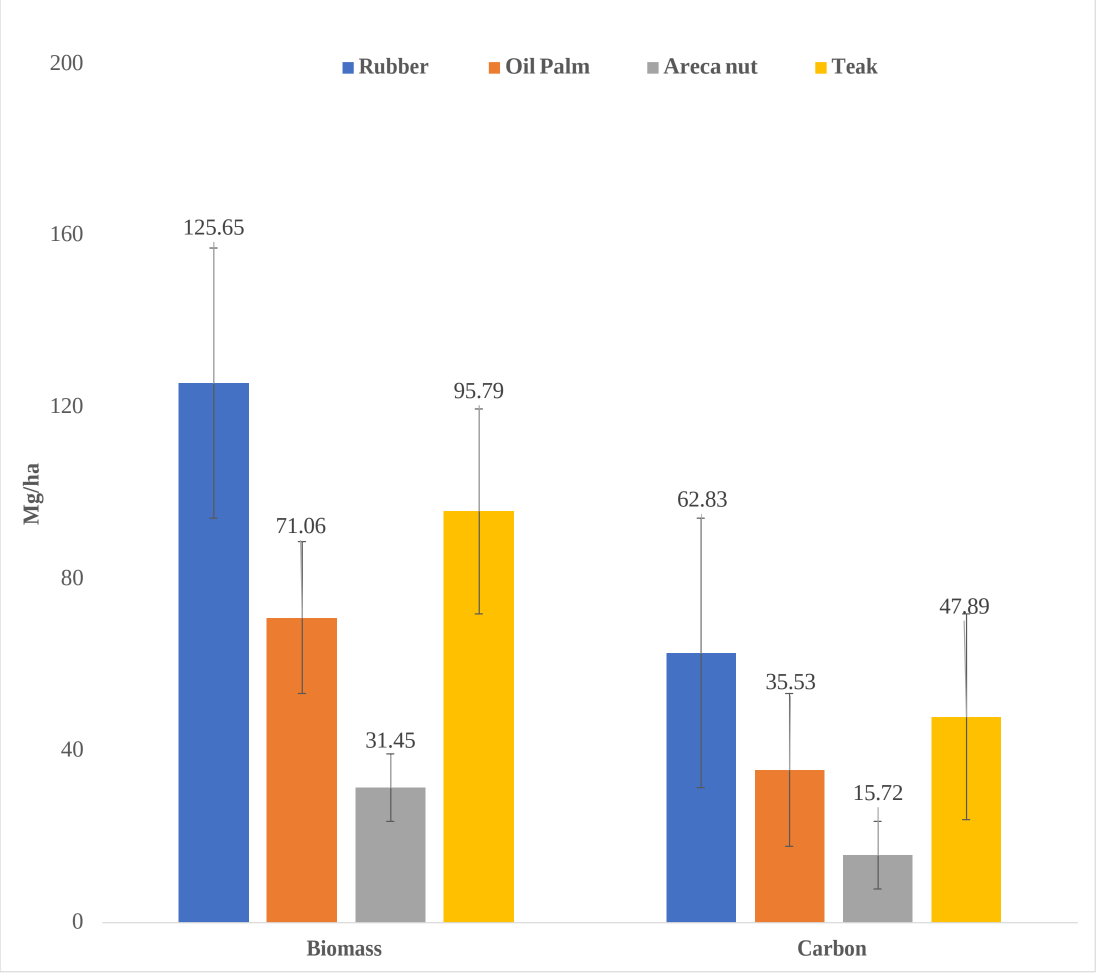


Figure 4.5: Total biomass and biomass carbon of selected plantations in Aizawl, Mizoram.

Table 4.3: Total biomass (Mg/ha) in different plantation selected for the study in Aizawl District of Mizoram.

Plantation	Living Biomass (Mg/ha)		Non-living biomass	Total biomass
	Above ground	*Below ground*		
Rubber	101.64 ± 3.46	24.36 ± 0.07	3.00 ± 0.07	129.00 ± 3.07
Oil Palm	57.79 ± 4.00	14.51 ± 0.07	2.53 ± 0.08	74.83 ± 4.85
Areca Nut	25.04 ± 3.62	6.67 ± 0.06	2.18 ± 0.08	33.89 ± 3.07
Teak	77.16 ± 3.62	18.88 ± 0.05	0.41 ± 0.10	96.45 ± 3.07
p- value	7.44	0.15	0.20	7.22

Table 4.4: Aboveground biomass across different pools (living trees, shrubs, litter and deadwood).

Plantation	Biomass (Mg/ha)				
	Trees	*Shrubs*	*Herbs*	*Litter*	*Deadwood*
Rubber	101.36 ± 4.57[a]	0.429 ± 0.02	0.521 ± 0.02	0.620 ± 0.05	1.027 ± 0.04
Oil Palm	56.844 ± 2.88	0.070 ± 0.01	0.304 ± 0.04[a]	0.728 ± 0.04	2.351 ± 0.16[a]
Areca Nut	24.839 ± 1.822[a]	0.003 ± 0.01	0.253 ± 0.01[a]	1.116 ± 0.30	0.491 ± 0.03[a]
Teak	76.963 ± 2.93[a]	0.003 ± 0.01	0.261 ± 0.01[a]	0.551 ± 0.03	0.272 ± 0.05[a]
p- value	0.026	0.354	0.043	0.234	0.022

*values followed after ± are standard error of man; a indicates significant difference between the plantation areas (Tukey HSD @0.05)

4.4.3. *Carbon stock of selected plantations*

The biomass carbon stock was seen to be the highest in rubber plantation (Figure 4.5) and the sequence was similar with the aboveground biomass order. One-way ANOVA showed a significant difference between the tree biomass carbon and post-hoc test results showed a significant variation between rubber and teak plantation ($p = 0.036$). The sequence of order on aboveground biomass carbon was rubber > teak > oil palm > areca nut (Table 4.5). One-way ANOVA revealed no significant differences between the shrubs and litter biomass carbon of the different plantations selected for this study.

The carbon stock of herbs in the selected plantations was highest in rubber plantation (0.261 ± 0.008 Mg ha^{-1}) which was proceeded by oil palm (0.151 ± 0.013 Mg ha^{-1}), teak (0.0130 ± 0.005 Mg ha^{-1}) and areca nut (0.126 ± 0.007 Mg ha^{-1}). The one-way ANOVA test showed a significant variation between the herbs‘ carbon amongst the different plantations and post-hoc test results indicated a significant variation between areca nut plantation and oil palm plantation (p=0.015). The deadwood biomass carbon was highest in oil palm plantation (1.175 ± 0.083 Mg ha^{-1}) and was preceded by rubber plantation (0.513 ± 0.018 Mg ha^{-1}), areca nut plantation (0.245 ± 0.015 Mg ha^{-1}) and teak plantation (0.137 ± 0.027 Mg ha^{-1}). Statistical analysis with one-way ANOVA indicated a significant variation between the selected plantations and post-hoc analysis depicted there was a significant variation between oil palm plantation and areca nut plantation (p=0.046) as well as teak plantation (p=0.023). Carbon storage in different components in the selected plantations are presented in Figure 4.6. Total carbon stock in rubber plantation (148.8 ± 19.45 Mg ha^{-1}) was found higher when compared to the other plantations, however, statistical variation between the plantations were not significant. Teak plantation proceeded rubber plantation with 142.9 ± 23.57 Mg ha^{-1} of total carbon stock, this was followed by areca nut plantation at 108.1 ± 19.45 Mg ha^{-1} with oil palm having the least total carbon stock at 97.0 ± 15.11 Mg ha^{-1}.

Table 4.5: Aboveground biomass carbon stock across different pools (living trees, shrubs, litter and deadwood).

Plantation	**Biomass Carbon Stock (Mg/ha)**				
	Trees	*Shrubs*	*Herbs*	*Litter*	*Deadwood*
Rubber	50.68 ± 2.235^{a}	0.215 ± 0.035	0.261 ± 0.008	0.400 ± 0.027	0.513 ± 0.018
Oil Palm	25.226 ± 1.685	0.035 ± 0.006	0.151 ± 0.013^{a}	0.364 ± 0.021	1.175 ± 0.083^{a}
Areca Nut	10.277 ± 0.873^{a}	0.001 ± 0.001	0.126 ± 0.007^{a}	0.558 ± 0.015	0.245 ± 0.015^{a}
Teak	38.482 ±2.233	0.001 ± 0.001	0.130 ± 0.005	0.276 ± 0.014	0.137 ± 0.027^{a}
p- value	0.038	0.300	0.043	0.234	0.022

*values followed after ± are standard error of man; a indicates significant difference between the plantation areas (Tukey HSD @0.05)

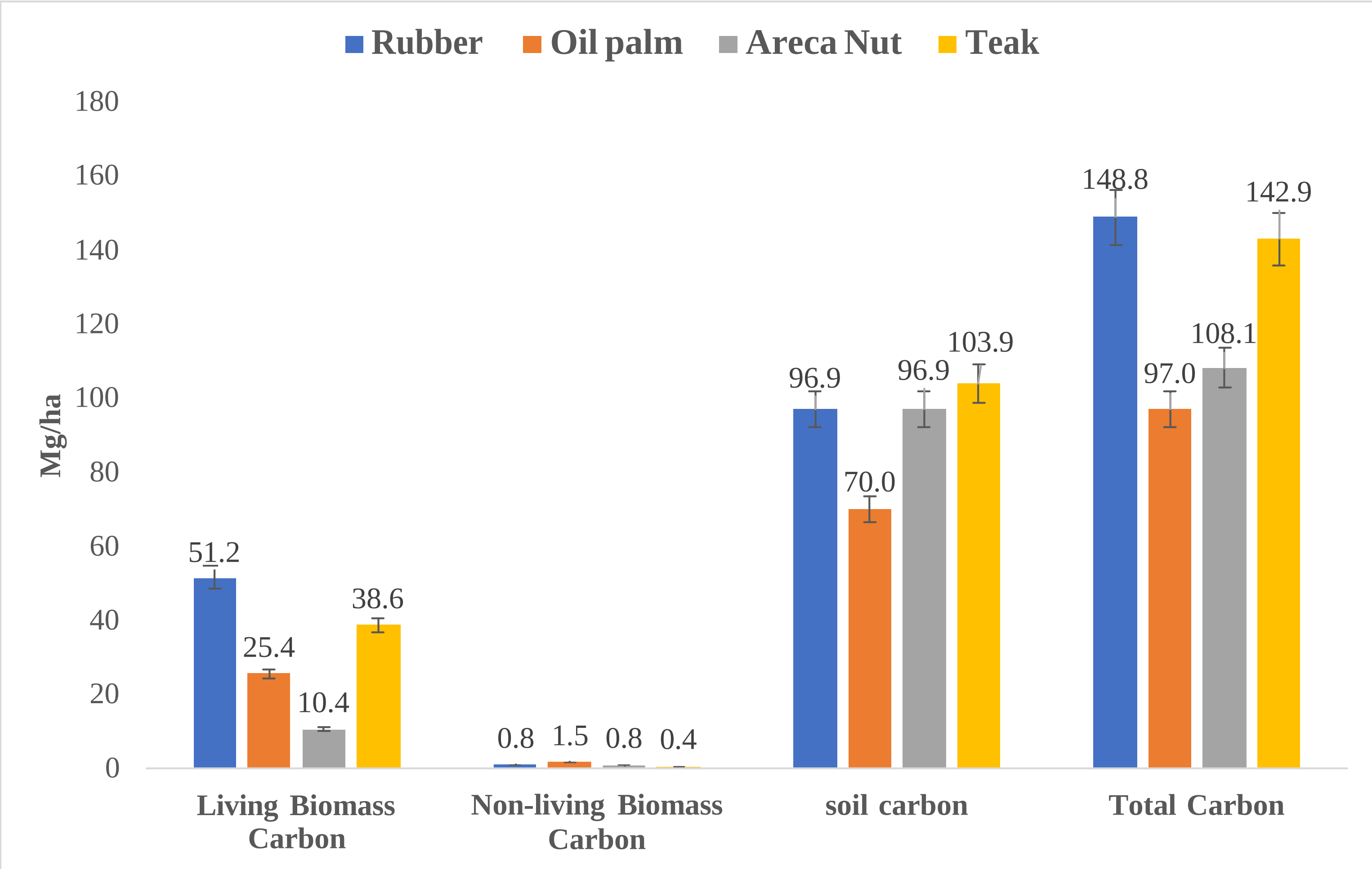
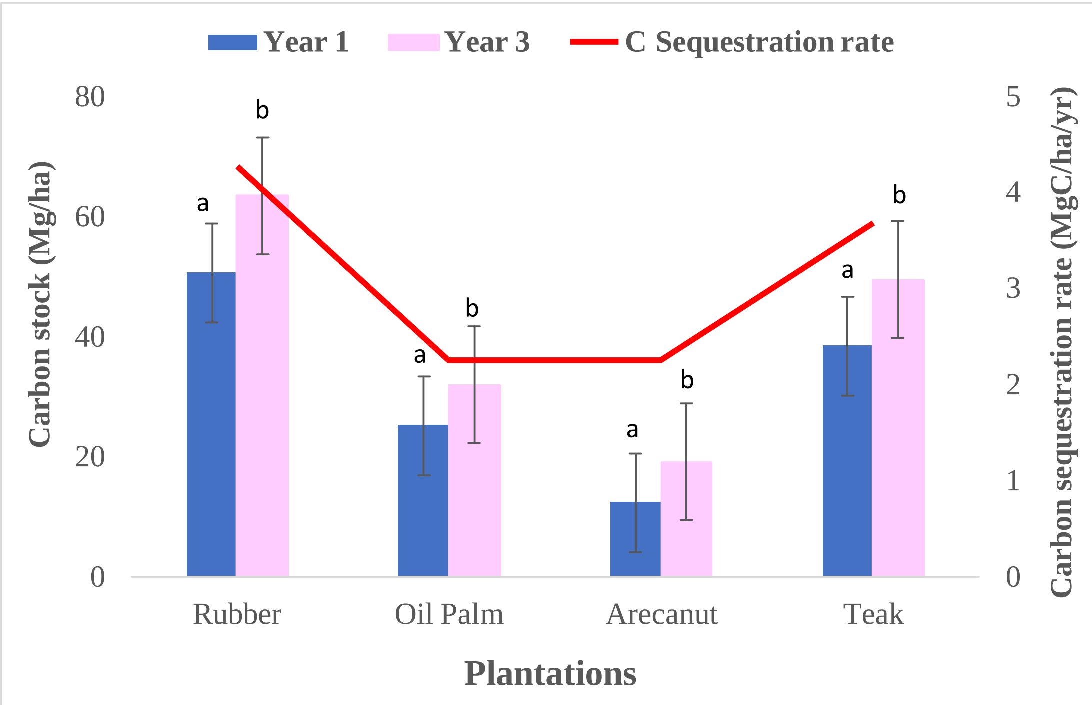


Figure 4.6: Carbon distribution in the different pools of the selected plantations in Aizawl, Mizoram

4.4.3. Carbon sequestration rate

The carbon sequestration rate showed no statistical variation between the four selected plantations, however, there was significant variation ($p<0.05$) between year 1 and year 3 of all the plantations (Figure 4.7). The carbon sequestration rate was the highest in rubber plantation (4.28 ± 0.24 Mg C ha^{-1} yr^{-1}), followed by teak plantation (3.68 ± 0.15 Mg C ha^{-1} yr^{-1}), areca nut plantation (2.50 ± 0.12 Mg C ha^{-1} yr^{-1}) and oil palm plantation (2.26 ± 0.33 Mg C ha^{-1} yr^{-1}). This showed that rubber plantation had the highest carbon sequestration potential among the selected four plantations and oil palm plantation had the least carbon sequestration potential.



*Different letters denote significant variation.

Figure 4.7: Carbon sequestration potential in the selected plantation sites in Aizawl, Mizoram

Table 4.6: Carbon sequestration rate in selected plantations during the study period

Plantation	Carbon sequestration rate (MgC/ha/yr)
Rubber	4.28 ± 0.24
Oil Palm	2.26 ± 0.33
Areca nut	2.50 ± 0.12
Teak	3.68 ± 0.15

4.4.4. CO_2 Potential of different plantations

The CO_2 potential in different plantations selected for the study showed rubber and teak were the highest and areca nut plantation has the least CO_2 potential (Figure 4.8). No statistical significance was observed between the plantations.

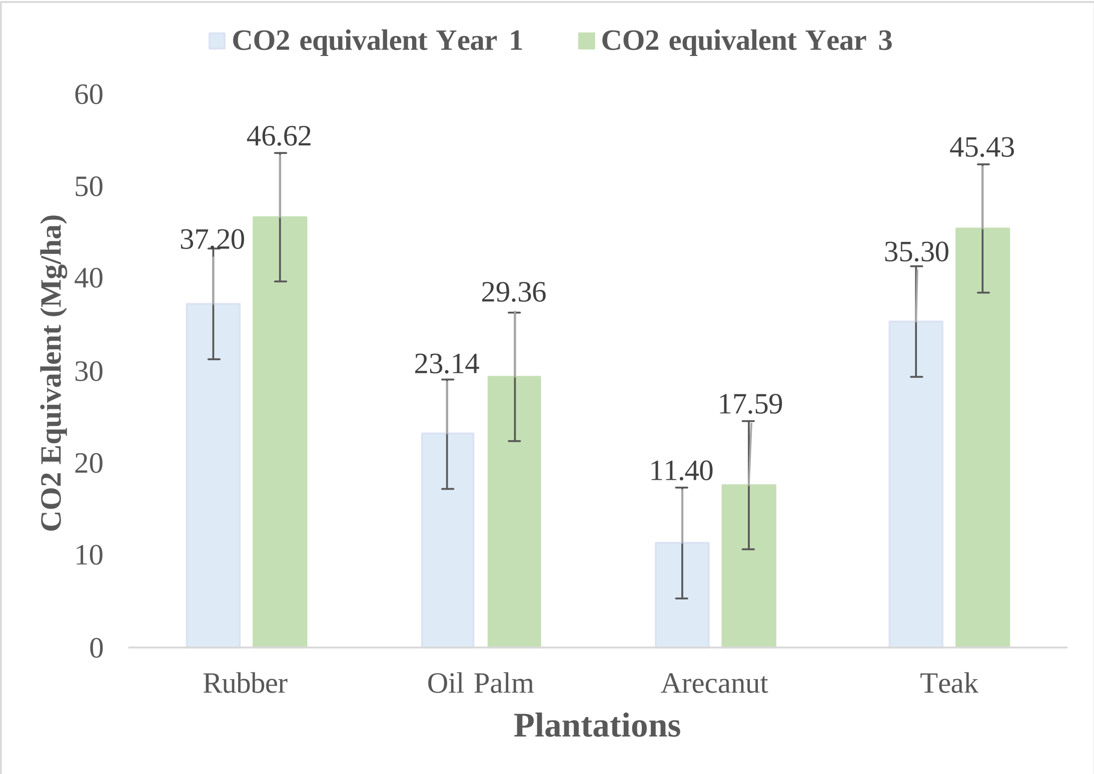


Figure 4.8: CO_2 equivalent values for the trees present in the selected plantations in Aizawl, Mizoram.

4.4 Discussion

Accurate estimation of carbon stocks and flux from different land use sectors is required for creating regional carbon inventory data sets as well as successful implementation of policy. For accurate estimation of carbon stocks of the selected four plantations, we used these proven formulas that are specifically developed for the north-eastern region of India. Biomass models based on only diameter at breast height (DBH) or with total height or wood density was used in predicting tree biomass, however, models containing either height or diameter predicted tree biomass correctly (Brahma et al., 2018). Biomass equation specifically developed for north-eastern for *Areca catechu* (Das et al., 2021) was used in this study. A precise measure of biomass was reported with the height of the areca tree than the DBH. Palms tend to exhibit primary growth in height that is not dependent of its diameter and the stems taper, thus the plant height can be predictive. The generalised biomass models for palms are available (Brown, 1997; Frangi & Lugo, 1985), yet, these models are lacking for Areca and oil palm especially in the north eastern region of India. These biomass models tend to over-estimate the biomass stock (Das et al., 2021). Teak and rubber plantation in the study exhibited high frequency distribution in 50-70 cm DBH class and studies done in plantations also showed that tree biomass differed significantly among the DBH classes, trees with circumferences 60-80 cm have lower and more variable biomass than those with circumferences of 80 cm or more (Brahma et al., 2018).

There have been various studies that highlighted both the positive and complex relation between diameter at breast height (DBH) and tree height. The selected plantations selected in our study apart from oil palm showed a positive relationship between the height and the DBH. The role of height and basal area (BA) in trees is critical for understanding forest dynamics, management, and ecological functions. Height and BA are interrelated metrics that influence tree growth, competition, and overall forest structure (Li et al., 2015). Large-diameter trees contribute significantly to the total BA in forests, providing essential ecosystem services such as carbon storage and habitat for wildlife (Seiwa et al., 2023). Height and BA can be effectively represented in management tools, allowing foresters to assess tree growth and determine thinning needs without age or site class as variables (Sijpesteijn, 1988). Height influences competition among trees, with taller trees often having an advantage in accessing resources, which can affect their growth rates (Biging & Dobbertin, 1995). The relationship between tree height and basal area are affected by species composition along with the environmental conditions. In young *Tectona grandis* plantations in Nigeria, basal area was effectively estimated using diameter at breast height and crown dimensions, with quadratic models providing robust estimates (Oyebade & Anaba, 2018). Although height and BA are vital for understanding tree growth and forest health, it is also crucial to consider the impact of environmental factors and species diversity, which can complicate these relationships.

Tree density and carbon stock was found intricately related, with variations in tree density significantly influencing carbon storage capabilities in forest plantations. Research indicates that higher tree densities can enhance biomass accumulation, thereby increasing carbon stocks, although this relationship can be complex and influenced by species and environmental conditions. Higher tree density is often associated with increased carbon storage (Sagar & Singh, 2006; Kayombo et al., 2022). Studies also suggested that denser forests enhanced soil carbon sequestration by contributing more litter and root-derived carbon inputs, while simultaneously reducing soil respiration and the decomposition of organic matter (Na et al., 2021). In tropical and temperate forest ecosystems, tree density can be significantly affected by carbon stocks, with denser forests exhibiting higher biomass carbon and sequestration potential (Das & Deb, 2022). However, the relationship can vary as in some cases, increased tree species richness negatively correlates with carbon stock, thus indicating that diversity may not always enhance carbon storage (Gurung et al., 2022). In addition, environmental factors such as soil properties and climatic factors play crucial roles in estimating carbon stock variability across different forest types (Ilboudo et al., 2022). Thus, effective forest management strategies that consider tree density can optimize carbon storage in various ecosystems.

The relationship between tree density and basal area tended to be positive as evidenced in various studies. In Tanzania, higher tree density was observed in woodland areas and exhibited a significant basal area, thus indicating that denser stands contributed to greater accumulation of biomass (Kayombo et al., 2022). Similarly, in northern India on disturbed dry tropical forests, tree density had a positive relationship with the total basal area (Sagar & Singh, 2006). Thus, the relation between tree density and basal area has a critical role in forest ecology, influencing management practices and conservation strategies and they are interconnected such that variation in one can affect the other. The basal area of trees contributed to the variation in the total living biomass. Diameter was used in the estimation of individual tree biomass in the study and a strong relationship between the biomass and basal area was found for the trees. Studies with similar findings have been reported elsewhere (Kayombo et al., 2022; Lin et al., 2015; Baraloto et al., 2011; Sagar & Singh, 2006). Numerous studies have also showed that the wood density has an important role in elucidating spatial variation in tree biomass and in most studies, a positive relationship between them (Kayombo et al., 2022; Sagar & Singh, 2006). Furthermore, the shift in forest structure and species composition due to forest disturbances were also accounted as crucial factors for forest biomass variations (Sagar & Singh, 2006). The amount of carbon stored in forest plantations is influenced by the structure and composition of the stand, as well as the disturbances acting upon them (Gogoi et al., 2017).

The biomass and carbon stock of plantations selected in our study was compared with similar studies done in north-eastern region on India as well as other areas of India. Values of rubber plantation in our study showed that the biomass and carbon stock was comparable with values (121.4 and 57.1 Mg ha^{-1} respectively) reported for Karimganj district of Assam (Brahma et al., 2018). The carbon sequestration rate, however, was slightly higher in our study compared to rate of rubber trees in Tripura (Sher Singh et al., 2023). Rubber plantation had the highest carbon storage among the plantations selected from our study area due to its greater biomass, soil organic carbon (SOC) as well as the large decomposition of branches and leaves on the site. Teak plantation also had a high carbon storage potential with the biomass and soil as the largest contributor. The biomass and carbon stock of teak plantation in the present study was also comparable with the values (78 and 39 Mg ha^{-1} respectively) to studies done in the *tarai* region of *Kumaun* Himalaya (Jha, 2015). However, when examining the values of similar aged teak plantation, those in southern region of India showed higher carbon stock (Reddy et al., 2014) with values of 108.5 Mg ha^{-1}.

The forest edaphic-climatic factors including the soil conditions, precipitation and temperature of teak plantation in the present study might have contributed to higher carbon stock and sequestration. Oil palm AGB accumulation rates, however, were lower than Singh et al., (2018) when accounting for palm mortality and replacements. Rainfall also affects carbon absorption, with higher rainfall during dry seasons correlating with increased carbon stocks in oil palm. Our finding for Areca biomass and carbon were comparable with Das et al., (2021) and Lewis et al., (2020). Areca plantation in Karimganj district, Assam for 10, 15, 25 and 35-years of age reported biomass values of 16.6, 39.2, 43.6 and 43.6 Mg/ha and carbon stock of 7.8, 18.4, 20.5 and 20.5 Mg/ha respectively (Das et al., 2021). However, these values are quite comparable with the present study for similar age group of plantations. The carbon sequestration rate of oil palm in the present study was slightly lower compared to the values reported by Singh et al., (2018a). Although AGB of AGB carbon of oil palm in the present study was comparable with study done in Assam (Das et al., 2021). When comparing other studies on rubber, the biomass of Areca with rubber, Areca plantations recorded 80% less biomass storage and a similar pattern can also be seen in our study (Brahma, et al., 2018). Areca plantations have low potential for biomass carbon storage and conversion of natural forests into such monoculture plantation can thus have a varied environmental impacts and disservice to the ecosystem, in particular, reduction of SOC stocks. This may cause reduction in biological diversity of soil along with its associated ecosystem services. Areca monoculture plantations tend to have lower infiltration, higher surface run-off and erosion when compared with natural forests (Das et al., 2021). However, the economic returns with the cash gain from different crops cultivated is often the drivers for these plantations (Sujatha et al., 2016). This may also be the reason for expansion of Areca nut plantation in northeast India including Mizoram.

4.5. Conclusion

The present study reveals that rubber plantation store more amount of biomass carbon compared to the other plantation crops. This was closely followed by teak plantation, while Areca nut plantation had the lowest biomass carbon stock amongst the selected sites. Though land use change from forests to monoculture may cause various ecosystem disservices, carbon storage by these plantation crops have been found to be of tremendous potential, something even better than the natural forests. Besides, the economic return from these crops (though not evaluated here) are the major reasons for their continuance and as a source of livelihood for the community.

CHAPTER V- ASSESSMENT OF SOIL PROPERTIES AND SOIL CARBON STORAGE OF SELECTED PLANTATIONS

5.1. Introduction

Forests can either act as a sink or source for carbon depending on carbon storage at release pattern. A forest can be a carbon sink when it absorbs more carbon from the atmosphere than it releases, while it can become a carbon source, if it releases large carbon into the atmosphere tan it absorbs. They play a key factor in the modification of atmospheric carbon (Kafy et al., 2023). They are converted into other land use types such as plantation or croplands through human activities – these anthropogenic activities have a detrimental impact on soil carbon storage (Fan et al., 2016; Sahoo et al., 2019) since it changes the properties of soil and its processes. In a study conducted in northern India, 21-36% of total organic carbon was lost in cultivated soils when compared to an uncultivated soil (Benbi et al., 2015) and this was found to be lesser from the values (30-60%) reported from various agro-climatic regions of India (Lal, 2004). The conversion of natural forests to croplands leads to disruption of soil structure which leads to SOC loss (Ajami et al., 2018). The largest carbon sink on earth is soil and they store ~1.5 x 103 Pg (1 Pg = 1015g) of carbon up to a depth of 1m. This is two and three folds higher than the atmosphere and total vegetation respectively (IPCC, 2006, 2007 & 2019) . Soil contributes to GHG emissions as a part of the carbon stored in soil is lost as carbon dioxide and methane to the atmosphere. A part of the GHG emissions can be mitigate by enhancement of soil organic carbon (SOC) sequestration through agricultural and monoculture management practices (Y.-Y. Yang et al., 2020). Introduction of tree crops in forest and agroforestry systems showed a significantly higher potential for SOC sequestration at longer time when compared with normal agricultural crops (Mayer et al., 2022).

Soil organic carbon (SOC) is influenced by numerous factors such as the land use, type of soil and climate (Borah & Parmar, 2024; Hrahsel & Sahoo, 2024; Yang et al., 2020). The quality of soil is related to the physical, chemical as well as biological attributes of soil and is influenced by management practices (Yang, et al., 2020). It is broadly well known that the amount of SOC is lower in sub-surface layers than the surface and greater in fine-textured soil than medium or coarse textured soils (Hrahsel & Sahoo, 2024). Additionally, the quantity of SOC typically increases with increase in annual precipitation and temperature because more water is available for plant growth and an increase temperature helps in better decomposition of organic matter (Hoyle et al., 2016). SOC can differ spatially and temporally due to the climate, flora and fauna, topography and lithological factors; these influence the loss and gain of the carbon in soil (Giardina & Ryan, 2000; Hrahsel & Sahoo, 2024). SOC can be treated as an important indicator of soil fertility, productivity and quality, since its decline can negatively impact land productiveness (Gogoi et al., 2017). In the recent years, there is a notable decline in soil productivity and large part of the SOC stock has suffered losses which is crucial for many vital ecosystem services (Uddin et al., 2022; Bagwan et al., 2023).

In the recent years, major conversion in land use is happening in Northeast India, where the natural forest in converted for shifting cultivation. About 85% accounts for shifting cultivation in Northeast India (Singh et al., 2018a), since it involves slashing and burning of natural forest, it will have a pernicious impact on soil organic carbon stock and soil health because of loss in biomass (Sahoo et al., 2019). There are studies which reported significant reduction in SOC stock on transforming natural forests for shifting cultivation (Singh et al., 2018 a; Singh & Sahoo, 2018; Kenye et al., 2019; Sahoo et al., 2019). Furthermore, the fallow cycle is shortened to facilitate the demands of the increasing population and posed a grave threat to ecology, crop production as well as land quality (Thong et al., 2018). More and more forests are converted for shifting cultivation due to majority of the households practicing it and is posing a great problem due to land degradation and the steep slope of the state (Sahoo et al., 2019). The soil health decreases by rendering it infertile and unproductive because of both shifting cultivation and steep slope of Mizoram. Policy makers such as Jhum Control Project and New Land Use Policy were adopted to provide alternatives, including agroforestry, plantation and horticulture (Sahoo et al., 2019). The role of plantations in carbon sequestration is crucial for climate change mitigation as understanding the SOC dynamics in different plantations can help policymakers and environmentalists develop strategies to enhance carbon storage in soils, thereby contributing to global carbon balance efforts (Hrahsel & Sahoo, 2024).

The changes in soil and vegetation influence the rate of carbon build-up or loss in soil (Poeplau & Dechow, 2023). Plantations account for 5% of global forest cover (FAO, 2011) and these are established at an accelerating rate throughout the world. There is an increasing need of conservation of plantations to reduce logging on natural forests, carbon sequestration and restoration of degraded land (Kothandaraman et al., 2022). Plantations such as rubber trees on degraded fallow lands have shown to supply large amount of carbon sink (Brahma et al., 2018). Globally as well as locally, many studies have suggested that SOC stock increases especially with the maturity of the stands (Choudhary et al., 2016; Brahma et al., 2018; Nath et al., 2018).

These plantations may be sustainable as well as provide economic security for the farmers involved in shifting cultivation if planted in their lands. Assessment of the overall SOC storage can provide information needed for climate change mitigation and adaptation in monoculture plantation. The present chapter provide us a better understanding of SOC in different plantation. The objective of the study was to estimate the SOC stock and selected soil properties as well as to analyse their inter-relationship between the different carbon fractions in soil of four plantations (rubber, oil palm, teak and areca nut) that have varying SOC stocks. The information gathered from this study may guide farmers and land planners in selecting appropriate tree species for plantations that optimize carbon storage and improve soil fertility (Hrahsel & Sahoo, 2024).

5.2. Methodology

5.2.1. Soil collection

In each of the four plantation, four quadrats (15 m x 15 m) were laid randomly and in each quadrat, soil was collected using an iron corer having a 5 cm diameter at a depth of 0-20 cm and 20-40 cm. A total of 32 soil samples were collected from each plantation at different soil depth. Samples were collected 1 m distance away from the trees. Undisturbed soil core samples were taken to the laboratory in a zip-lock bag and were used for analyzing their bulk density. The soil samples were also air dried and passed through a 2 mm sieve and were further used for analyzing their physicochemical properties.

5.2.2. Soil pH

The pH is a measure of hydrogen or hydroxyl ion activity of the soil-water system and indicated whether the soil is acidic, neutral or alkaline. Soil pH was measured using soil-water suspension at the ratio of 1:2.5 using a digital pH meter. 10g of soil sample was taken in a 50 ml beaker and 25 ml of distilled water was added and stirred for five minutes. This was kept for 30 minutes and was stirred again before the pH reading was taken.

5.2.3. Soil Moisture

Soil moisture content was estimated gravimetrically by oven drying 10 g of fresh soil at 105°C for 48 hours to constant weight. The moisture content was expressed in percentage (%)

5.2.4. Bulk density

Bulk density was measured using corer method (Brady & Weil, 2017) where undisturbed soil cores were collected in the field. Soils from different depth class were taken with a soil corer of volume 475.167 cm^3. The soil samples were taken to the laboratory in a zip-locked bag and its fresh weight was measured. The soil samples were then air-dried with the roots and other plant materials removed, this was kept in the oven at 105°C for 72 hours or till the constant weight was achieved. After attaining constant weight, it was further divided by volume of corer and the bulk density of soil was obtained. The oven-dried soil samples were grounded and sieved through a 2 mm sieve to estimate the coarse rocky fragment percentage.

5.2.5. Soil Organic Carbon (SOC) and SOC Stock

Soil organic carbon was determined by Walkley & Black (1934) rapid titration method and the SOC stock was determined by considering SOC concentration, bulk density (corrected for coarse fraction) and soil depth using the following equation (Sahoo et al., 2019):

$$\text{SOC stock (Mg ha}^{-1}) = [\text{SOC\%} \times \text{corrected BD (Mg m}^{-3}) \times \text{T (m)} \times 10^{4}(\text{m}^{2}\ \text{ha}^{-1})]/100$$

The concentration of organic carbon was determined using the three acid-aqueous solution ratios, which allowed the separation of TOC into the following four fractions of decreasing oxidizable /lability (Sahoo et al., 2019):

1. Very labile carbon (VLC): Organic carbon oxidizable under 12N H_2SO_4
2. Labile carbon (LC): Difference in SOC oxidizable under 18N and that under 12N H_2SO_4
3. Less labile carbon (LLC): Difference in SOC oxidizable under 24N and that under 18N H_2SO_4
4. Recalcitrant/ non-labile carbon (NLC): Residual SOC after reaction with 24N H_2SO_4 when compared with TOC.

The very labile and labile carbon pool was summarized as active carbon pool and less labile and non-labile carbon pool were summed as passive carbon pool.

5.2.6. Total Carbon

Total Carbon of soil was measured by Vario TOC Analyzer (IR type analyzer). The soil samples were injected into a combustion tube which was enriched with oxygen. Carbon that was present in the sample was converted to carbon dioxide at 950°C in the presence of copper oxide (Bisutti et al., 2004).

5.2.7. Available Nitrogen

Available nitrogen was determined by Subbiah & Asija (1956) method where the nitrogen that was easy to mineralize was estimated using alkaline potassium permanganate solution ($KMnO_4$). $KMnO_4$ solution oxidized the organic matter present in the soil and hydrolyzed the liberated ammonia (NH_4), this was further condensed further absorbed in boric acid which was eventually titrated against standard acid.

5.2.8. Calcium and Magnesium

Calcium and Magnesium are essential nutrients to plants and are widely distributed and abundant elements in soil. They share common chemical properties such as their natural occurrence - carbonate, phosphate, sulphate or silicates, and they precipitate in similar way. Calcium is absorbed by plants as Ca^{2+} from soil and although Ca deficiency is quite uncommon, it can occur is an extremely leached and un-limed acid soil. The concentration of Ca^{2+} is ten times greater than potassium (K^+), its intake is generally less than that of potassium. Calcium and Magnesium was estimated using ammonium acetate extracts of soils by EDTA Titrimetric method (Tucker & Kurtz, 1961), they both can be titrated at a pH of 10 using Eriochrome black T (EBT) as an indicator.

5.2.9. Potassium

Potassium in soil is water soluble, exchangeable, non-exchangeable and lattice-K. Exchangeable potassium exceeds the amount of water-soluble potassium present in soil. Ammonium acetate method (Hanway & Heidal, 1952) was used for estimating exchangeable potassium present in the soil. Flame photometer was used in this method as the ammonium acetate burns with no residue leaving only the potassium to be estimated.

5.3. Statistical Analysis

Analysis of data was performed using Microsoft Excel 2019 (Version: 16.79.2), SPSS (IBM SPSS Statistics 25) and Janmovi (2.3.28). One-way and two-way ANOVA were performed between the different plantations and soil depth along with the various soil parameters. Test of significance was performed using Tukey‘s HSD with $p \leq 0.05$, where p value greater than 0.05 were rejected. SPSS was used for estimating Pearson‘s correlation and analysis of variance.

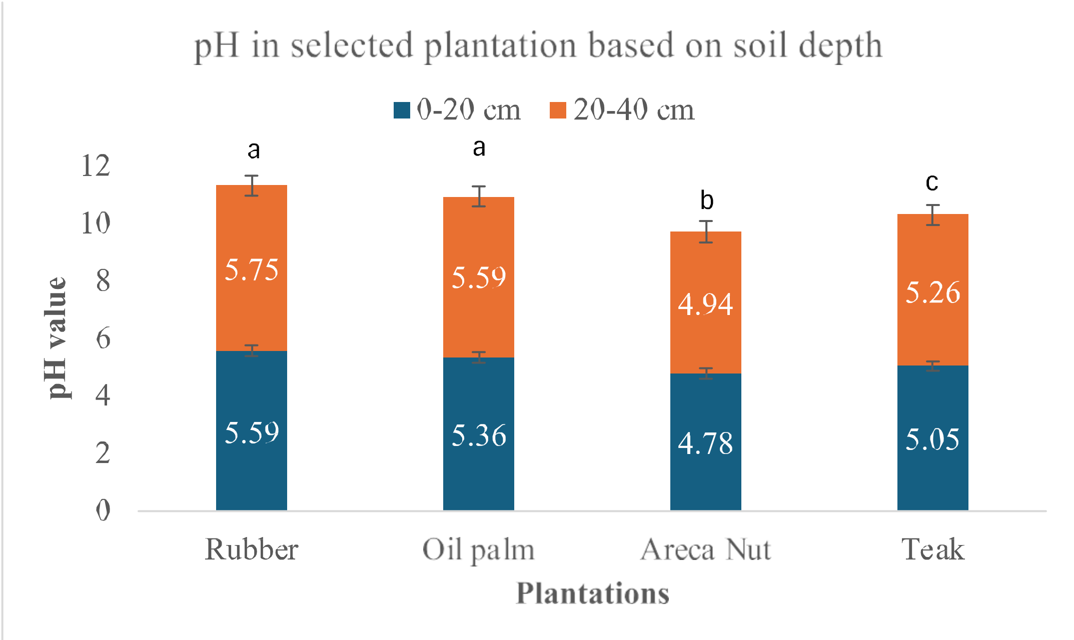
5.4. Results

5.4.1. Physico-chemical properties of soil

The physico-chemical properties of the soil in the four different plantation are presented in Table 5.1. These soil properties specify the significant differences among the plantations and the depth of the soil (Table 5.2), however, there was no significant relationship between plantation and soil depth except in soil organic carbon (SOC) stock. In the four plantations, significant ($p < 0.005$) variations were observed in the soil properties along with the soil depth (Table 5.2).

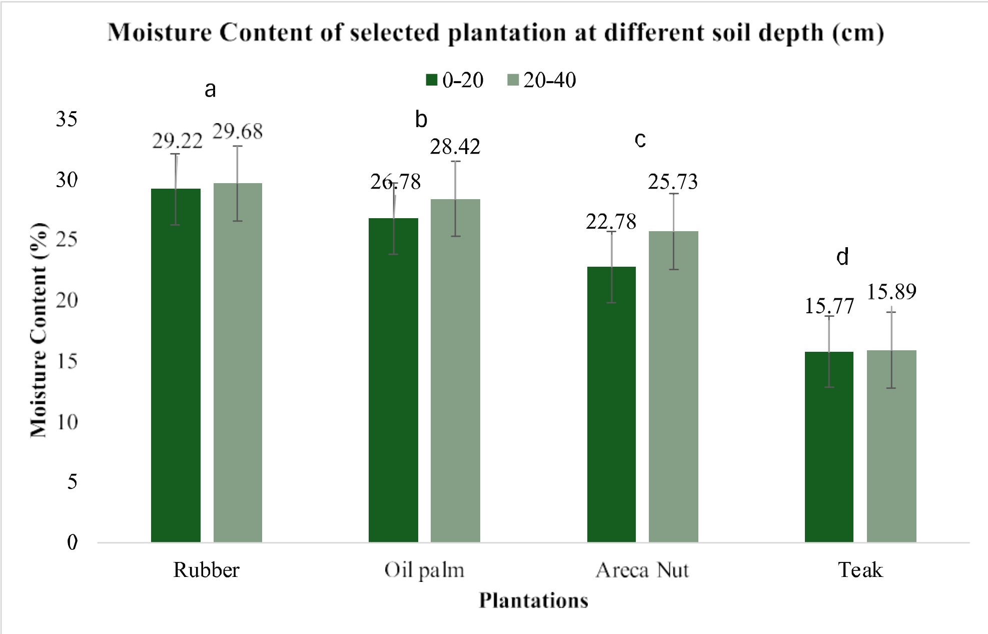
The pH of all plantations was mildly acidic, and they follow a similar pattern since they all increased with the increase in depth of the soil. There was a significant variation between the pH of areca nut plantation with rubber and teak plantation. The value of pH ranged from 4.79 – 5.46 in 0-20 cm soil depth and 4.93 – 5.64 in 20-40 cm soil depth (Figure 5.1). Areca nut plantation was found to have the lowest pH amongst the selected plantations with pH at 4.78 in 0-20 cm soil depth and 4.94 in 20-40 cm soil depth. The highest pH was seen in rubber plantation with 0-20 cm soil depth having pH value of 5.59 and 20-40 cm depth with pH 5.75. There were no significant differences between rubber and oil palm plantation while significant differences between areca nut and teak plantation with rubber and oil palm were observed.

The moisture content and bulk density was found increasing with the increase in soil depth. These also significantly ($p < 0.005$) varied between the plantations (Table 5.2). These values were the lowest in teak plantation (soil moisture less than 20%) and highest in rubber plantation (Figure 5.2). The moisture content was seen in the following order: Teak < Areca Nut < Oil Palm < Rubber (Figure 5.2), whereas the bulk density was in the order: Oil Palm < Areca nut< Teak < Rubber (Figure 5.3). It was observed to be the lowest in oil palm plantation and showed significant variations ($p < 0.005$) between oil palm plantation with rubber and teak plantations and the bulk density increased with the depth of the soil. Here, the soil too exhibited a positive relationship with the bulk density (Table 5.3). The results revealed a specific trend of its bulk density increasing with the increase in depth of the soil (Figure 5.3). there was also a positive correlation between the bulk density and the depth of the soil which showed that bulk density increased with increase in soil depth. A significant variation between the bulk density of the oil palm plantation with rubber and teak plantation was also observed.



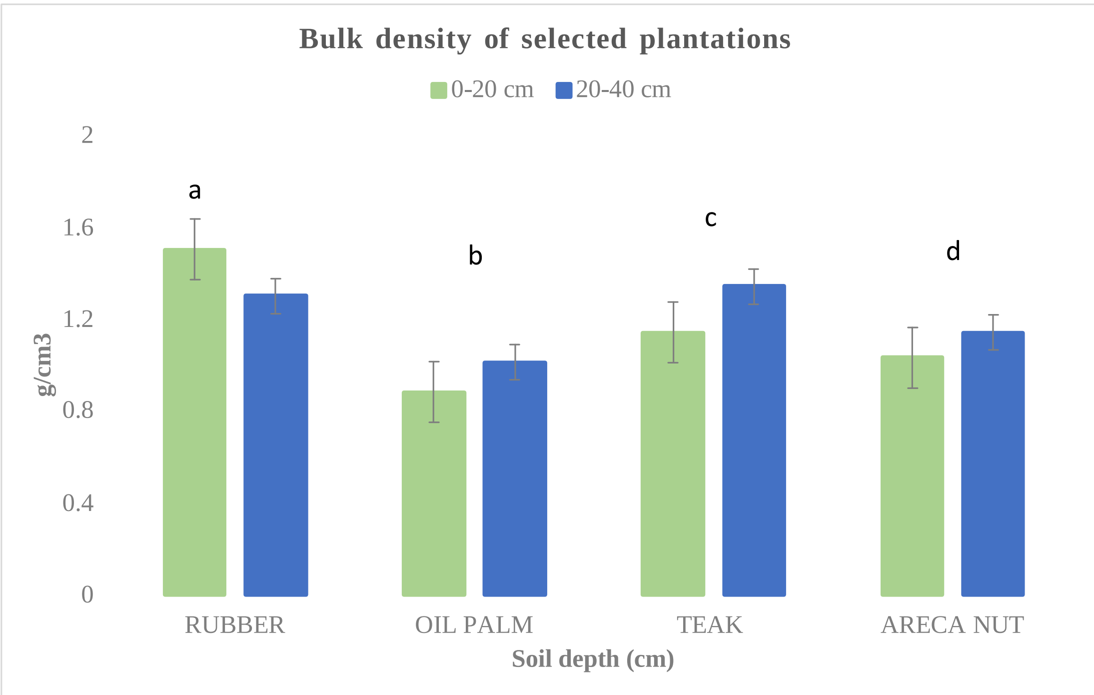
Different letter denote significant variation between the plantations (Tukey HSD @0.05)

Figure 5.1: pH of selected plantations in different soil depth.



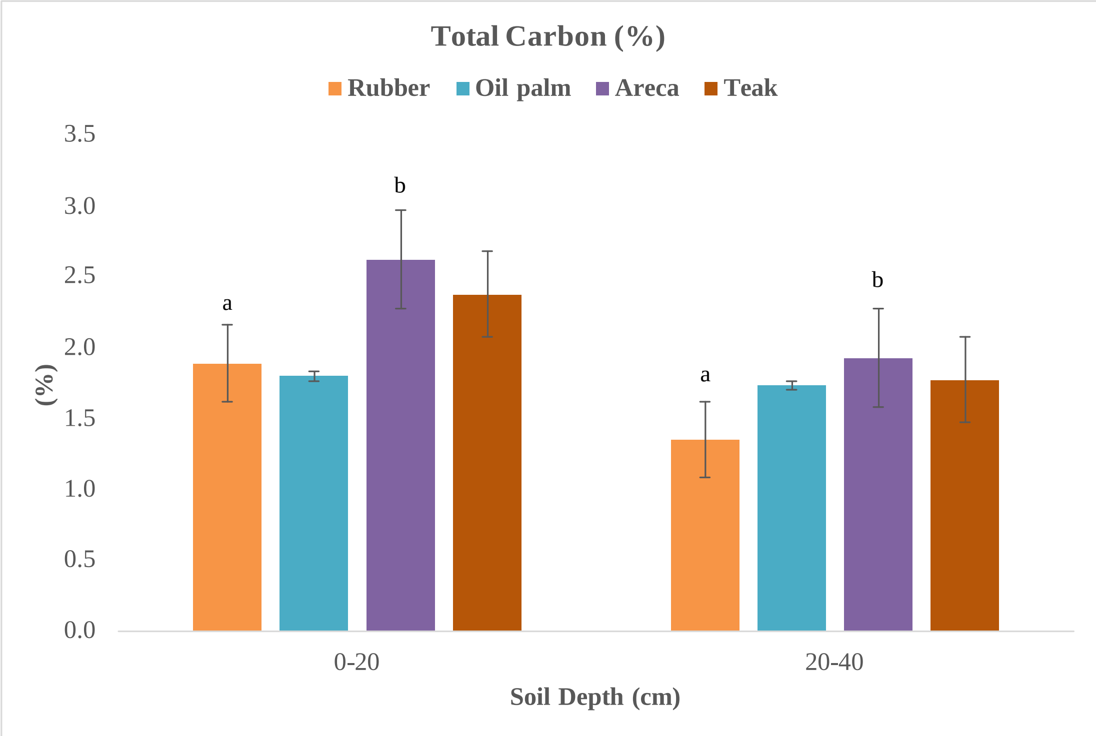
Different letters denote significant differences between the plantations (Tukey HSD @0.05)

Figure 5.2: Moisture content (%) of selected plantations at different soil depths (cm).



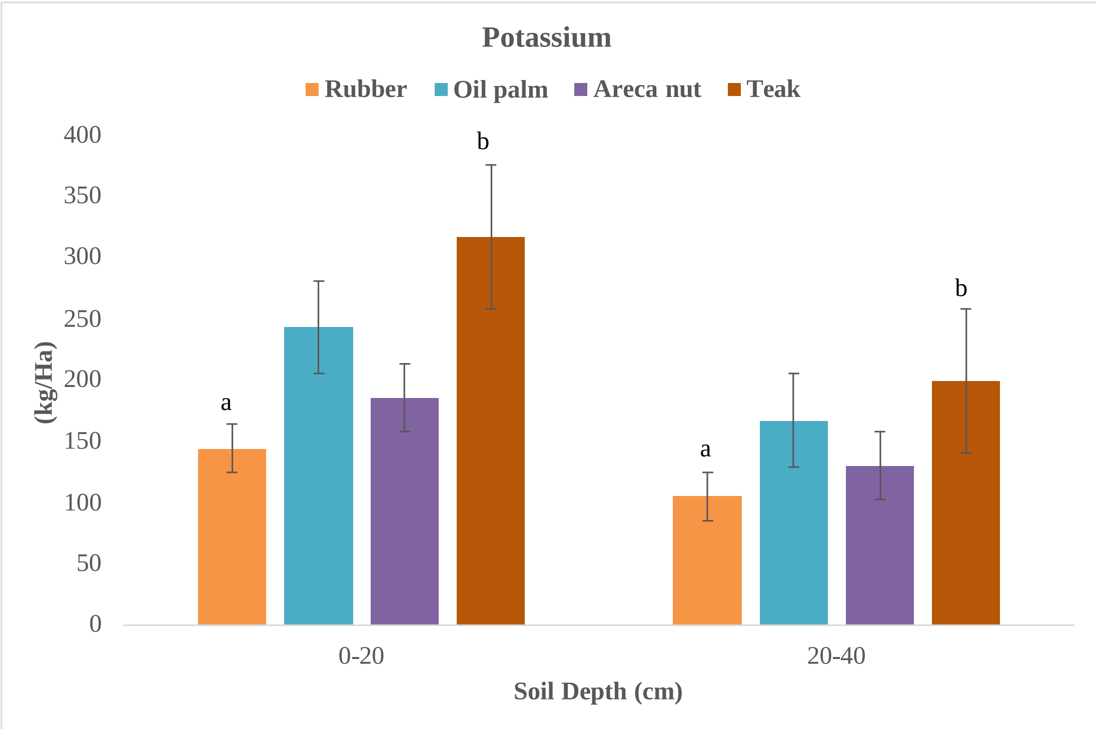
Different letters denote significant differences between the plantations (Tukey HSD @0.05)

Figure 5.3: Bulk density (g/cm^3) of selected plantations at different soil depths (cm).



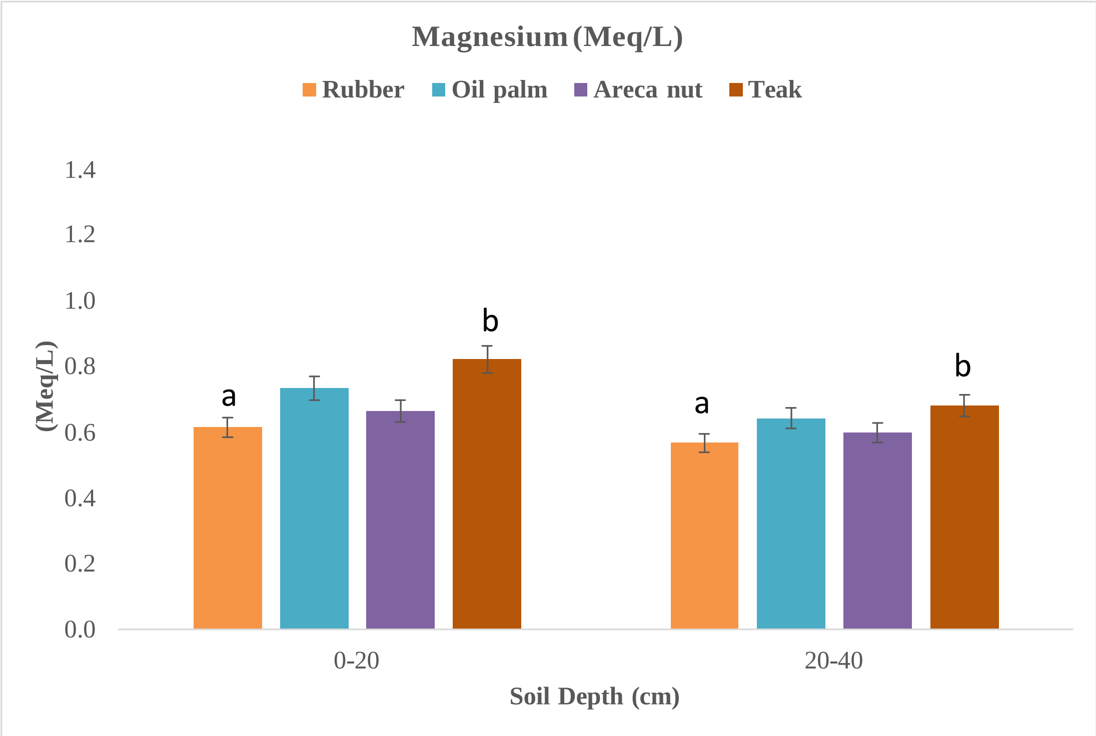
Different letter denotes significant variation between plantations and soil depth (Tukey HSD @0.05)

Figure 5.4: Total carbon (%) across selected plantations of the study sites in Mizoram.



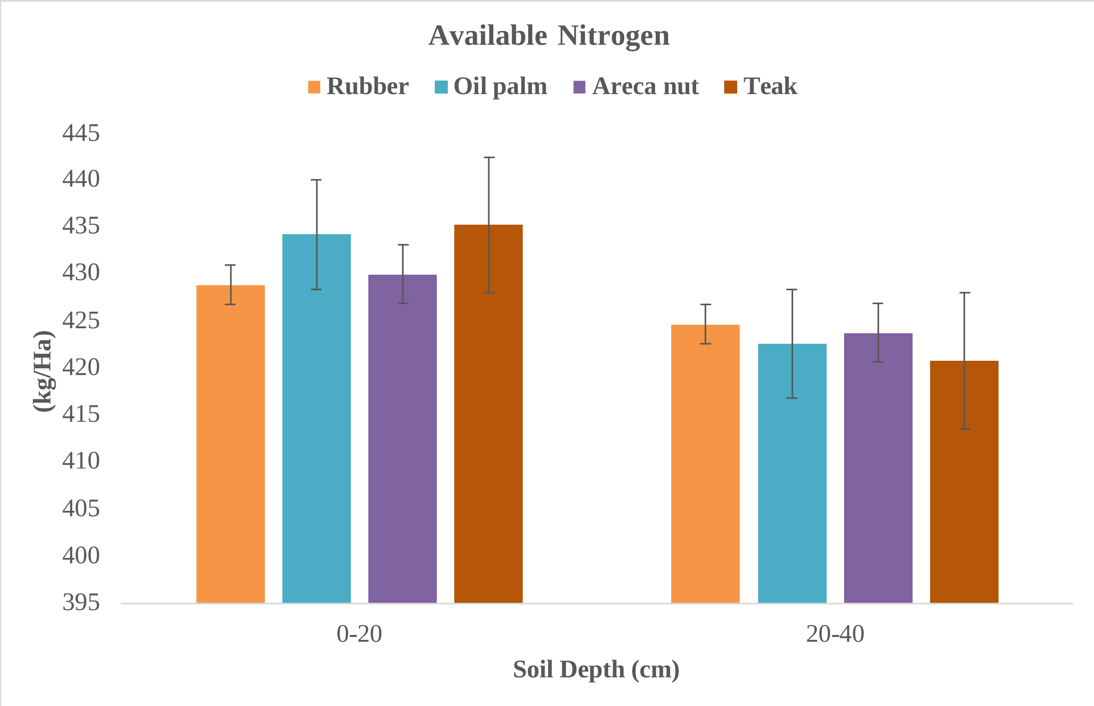
Different letter denotes significant variation between plantations and soil depth (Tukey HSD @0.05)

Figure 5.5: Potassium content (kg/ha) across selected plantations of the study sites in Mizoram



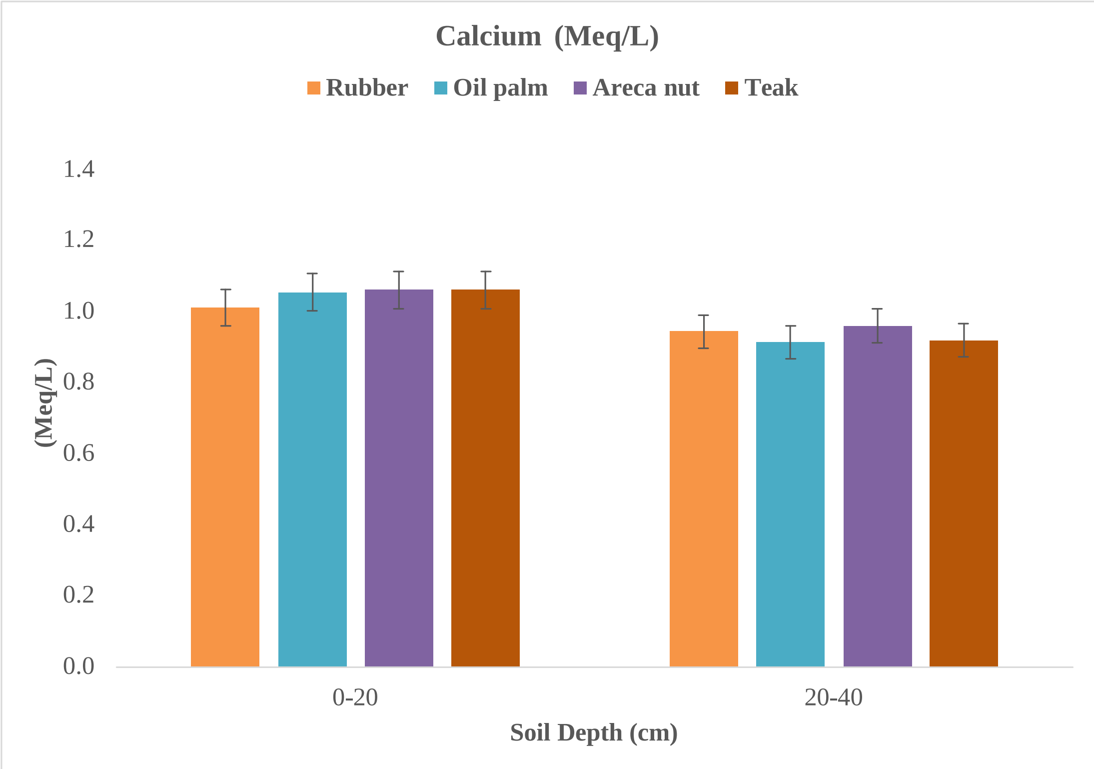
Different letter denotes significant variation between plantations and soil depth (Tukey HSD @0.05)

Figure 5.6: Magnesium content (Meq/L) across selected plantations of the study sites in Mizoram



Different letter denotes significant variation between plantations and soil depth (Tukey HSD @0.05)

Figure 5.7: Available nitrogen content (kg/ha) across selected plantations of the study sites in Mizoram.



Different letter denotes significant variation between plantations and soil depth (Tukey HSD @0.05)

Figure 5.8: Calcium content (Meq/L) across selected plantations of the study sites in Mizoram.

Table 5.1: Soil physico-chemical properties in different plantation

Soil Properties	RUBBER		OIL PALM		TEAK		ARECA NUT	
	0-20 cm	**20-40 cm**	**0-20 cm**	**20-40 cm**	**0-20 cm**	**20-40 cm**	**0-20 cm**	**20-40 cm**
pH	5.46 ± 0.15[a]	5.64 ± 0.15[a]	5.36 ± 0.15[a]	5.59 ± 0.15[a]	5.05 ± 0.15	5.26 ± 0.15	4.78 ± 0.15[a]	4.93 ± 0.15[a]
Moisture (%)	29.58 ± 1.78[a]	30.05 ± 1.78[a]	26.78 ± 1.78[a]	28.42 ± 1.78[a]	15.77 ± 1.78[a]	15.89 ± 1.78[a]	22.78 ± 1.78[a]	25.73 ± 1.78[a]
BD(g/cm^3)	1.17 ± 0.08[a]	1.32 ± 0.08[a]	0.88 ± 0.08[a]	1.01 ± 0.08[a]	1.14 ± 0.08[a]	1.34 ± 0.08[a]	1.03 ± 0.08	1.14 ± 0.08
SOC (%)	1.92 ± 0.20	1.17 ± 0.20	1.47 ± 0.20	1.66 ± 0.20	1.61 ± 0.20	1.47 ± 0.20	1.97 ± 0.20	1.64 ± 0.20
SOC Stock (MgC/h)	45.03 ± 5.16[a]	31.23 ± 5.16[a]	26.05 ± 5.16	34.31 ± 5.16	49.09 ± 5.16[a]	28.98 ± 5.16[a]	30.08 ± 5.16[a]	27.73 ± 5.16[a]
TC (%)	1.85 ± 0.20[a]	1.35 ± 0.20[a]	1.79 ± 0.20	1.73 ± 0.20	2.37 ± 0.20	1.77 ± 0.20	2.62 ± 0.20[a]	1.92 ± 0.20[a]
Avl. N (kg/h)	428.79 ± 3.32	424.63 ± 3.32	434.14 ± 3.32	422.55 ± 3.32	435.14 ± 3.32[a]	420.69 ± 3.32[a]	429.89 ± 3.32	423.67 ± 3.32
K (kg/h)	144 ± 46.18[a]	104.84 ± 46.18[a]	243.06 ± 46.18	167.04 ± 46.18	316.77 ± 46.18	199.29 ± 46.18	185.47 ± 46.18	130.18 ± 46.18
Mg (Meq/L)	0.615 ± 0.05[a]	0.57 ± 0.05[a]	0.73 ± 0.05	0.64 ± 0.05	0.82 ± 0.05[a]	0.68 ± 0.05[a]	0.66 ± 0.05	0.60 ± 0.06
Ca (Meq/L)	1.01 ± 0.04	0.94 ± 0.04	1.05 ± 0.04	0.91 ± 0.04	1.06 ± 0.04	0.92 ± 0.04	1.06 ± 0.04	0.96 ± 0.04

BD= bulk density; SOC= soil organic carbon; TC= total carbon; N= available nitrogen; K= potassium; Mg= magnesium; C= calcium; *values followed after ± are standard error of man; a indicates significant difference between the plantation areas (Tukey HSD @0.05)

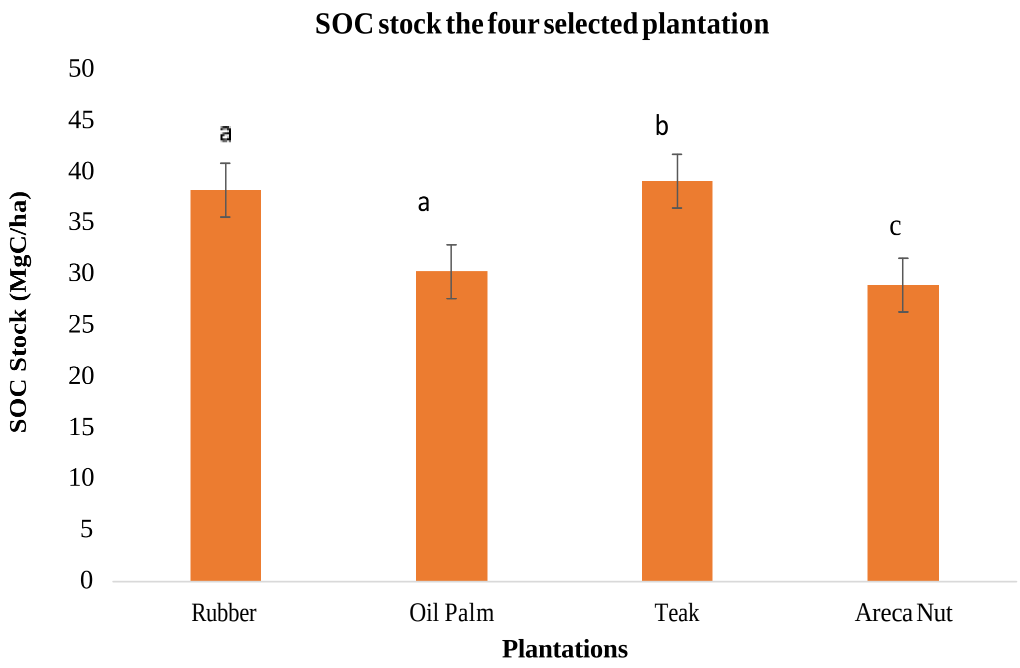
Table 5.2: Two-way ANOVA showing significant differences in soil characteristics.

Source	pH	Moisture (%)	BD (g/cm^3)	SOC (%)	SOC Stock (MgC/h)	TC (%)	Avl. N (kg/h)	K (kg/h)	Mg (Meq/L)	Ca (Meq/L)
Plantation	8.836*	23.892*	5.794*	0.127	4.001*	4.243*	0.122	3.168*	3.18*	0.303
Soil Depth	3.379	1.064	6.317*	0.383	2.469	10.963*	15.026*	4.859*	5.101*	19.567*
Plantation x Soil depth	0.028	0.26	0.106	2.442	3.772*	0.96	1.022	0.269	0.278	0.482

BD= bulk density; SOC= soil organic carbon; TC= total carbon; N= available nitrogen; K= potassium; Mg= magnesium; C= calcium; Values present F values; *indicate significant differences between the physico-chemical properties with plantation and soil depth (Tukey HSD @0.05)

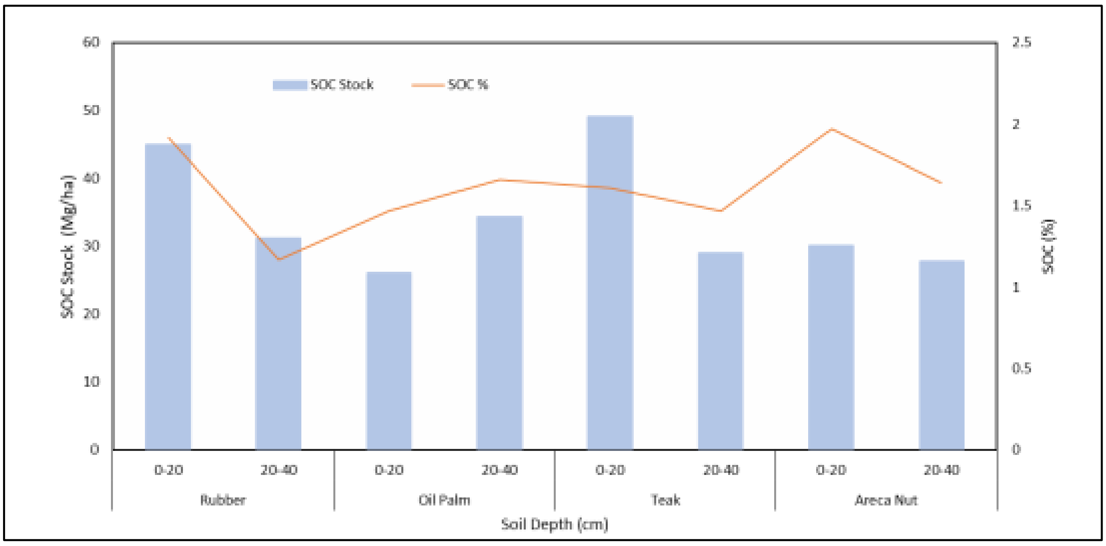
5.4.2. SOC Concentration of SOC Stock

SOC concentration was found in the range 1.17 – 1.92 (%) while the SOC stock was found ranged from 26.05 – 49.09 (Mg C/ha) among the plantations. Furthermore, there were dissimilarity between areca nut plantation with rubber and teak plantation in their SOC stock content. All the plantations except oil palm plantation showed a decrease in SOC concentration and SOC stock with the increase in soil depth. The total carbon only exposited a significant difference between the rubber plantation and areca nut plantation, while potassium and magnesium showed disparity between the rubber and teak plantation (Table 5.2). Plantation type and their interaction with soil greatly influenced the soil properties as well as their SOC content in the soil (Figure 5.4). However, it was found in our study that the SOC concentration and SOC stock in the plantations did not indicate any trend with the depth of the soil (Figure 5.4). The SOC stock observed in our study showed a significant variation ($p < 0.05$) in all the plantations except oil palm plantation (Figure 5.5). All the plantations recorded lower total carbon (TC) with the increment of soil depth. This trend was also noted in other soil parameters such as available nitrogen where the highest range was 435.12 (kg/ha) in 0-20 cm depth and 424.63 (kg/ha) in 20-40 cm depth and the highest values were both from the rubber plantation selected in this study. However, no discernible variation was found between the different plantation soils in their SOC concentration (%), available nitrogen and calcium contents of the different plantations. For total carbon, significant variations between rubber and areca nut plantations were observed at both the soil depth (Figure 5.7). Similarly, it was also the case for potassium and magnesium, between rubber and teak in both the soil depths (Figure 5.8 and 5.9). All the plantations showed a decline in their potassium, magnesium and calcium concentration with the soil depth and a negative relationship was observed between these soil properties and the depth of the soil (Table 5.3).



Different letter denotes significant variation between plantations and soil depth (Tukey HSD @0.05)

Figure 5.9: SOC stock (Mg C/ha) of selected plantations in Mizoram.



Different letter denotes significant variation between plantations and soil depth (Tukey HSD @0.05)

Figure 5.10: SOC stock vs. SOC (%) of selected plantations at different soil depths (cm).

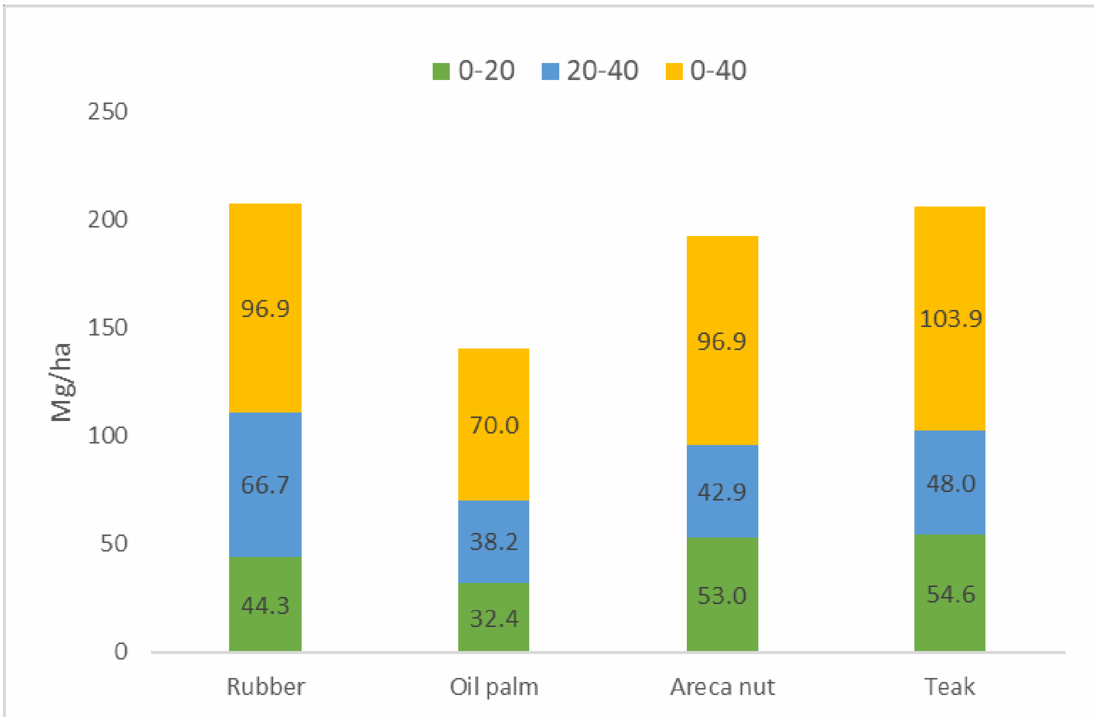


Figure 5.11: SOC Distribution in the different layers of soil within the selected plantations of Aizawl, Mizoram.

5.4.3. Relationship between soil parameters and carbon fractions in SOC

The correlation matrix between the soil depth with soil properties (Table 5.3) showed a significant positive relationship with the bulk density ($p < 0.05$) and negative relations with the total carbon, available nitrogen and calcium ($p < 0.01$) along with potassium, magnesium ($p < 0.05$). SOC stock was observed to have a positive relationship with bulk density and SOC concentration ($p < 0.01$) and negative correlation with calcium. SOC concentration (%) in the very labile carbon at 0-20 cm depth showed variation between rubber and teak plantation as well as areca nut and teak plantation (Table 5.4) at $p< 0.05$. However, at 20-40 cm depth, no significant variation was observed. Areca nut plantation had the highest amount of very labile carbon in both the soil depths. Labile carbon at 0-20 cm depth showed significant variation between rubber and areca nut plantation, however at 20-40 cm depth it did not show significant variation. Areca nut plantation had the highest labile carbon at 0-20 cm soil depth and in oil palm it showed the highest at 20-40 cm depth. For less labile carbon, differences between rubber and areca nut plantation were observed at 20-40 cm depth but no significance between was seen the plantations at 0-20 cm depth. Rubber plantation contributed the most in less labile carbon for both the soil depths. No statistically significant variation was seen in non-labile carbon at both the soil depths and rubber was the largest amount of non-labile carbon in both the soil depths.

Table 5.3: Pearson's correlation between soil depth and soil properties.

Correlations	SOC (MgC/ha)	pH	Moisture content (%)	Bulk density (g/cm3)	Total Carbon (%)	Available Nitrogen (kg/ha)	Potassium (kg/ha)	Magnesium (Meq/L)	Calcium (Meq/L)
SOC (MgC/ha)	1								
pH	0.212	1							
Moisture content (%)	-0.119	.436*	1						
Bulk density (g/cm3)	.601**	0.128	-0.265	1					
Total Carbon (%)	0.1	-0.34	-0.218	-0.183	1				
Available Nitrogen (kg/ha)	-0.264	-0.3	-0.013	-0.327	0.144	1			
Potassium (kg/ha)	-0.236	-0.26	-0.327	-0.08	0.137	0.338	1		
Magnesium (Meq/L)	-0.234	-0.26	-0.328	-0.079	0.134	0.341	1.000**	1	
Calcium (Meq/L)	-0.32	-0.21	-0.001	-0.258	.425*	.387*	.633**	.636**	1

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed).

5.4.4. Active and passive carbon pools

Very labile and labile pool was summed as active pool and less labile and non-labile was summed as passive pool. The organic carbon pool for the selected plantations showed higher active carbon pool than the passive carbon pool (Table 5.5). Areca nut plantation had the highest very labile carbon pool while the lowest was observed in rubber plantation. However, the labile carbon was lowest in areca nut plantation. Less labile carbon was the least in oil palm plantation, but rubber plantation had the largest less labile carbon on the other hand, rubber plantation had the highest non-labile carbon, and the least was found in oil palm plantation. In the active carbon pool, no significant variation was observed between the selected plantations although passive carbon pool showed variation between oil palm and the three other selected plantations (Table 5.5).

Table 5.4: SOC Concentration (%) of varying labilty at different soil depth classes in different plantations of Aizawl, Mizoram.

Plantation	Very Labile Carbon		Labile carbon	
	0-20	20-40	0-20	20-40
Rubber	0.74 ± 0.10 [a]	0.57 ± 0.09 [a]	0.26 ± 0.11 [ab]	0.87 ± 0.31 [a]
Oil Palm	0.88 ± 0.07 [a]	0.93 ± 0.12 [a]	0.50 ± 0.11 [a]	0.58 ± 0.06 [a]
Areca Nut	1.36 ± 0.06 [ab]	1.16 ± 0.10 [a]	0.57 ± 0.04 [b]	0.36 ± 0.07 [a]
Teak	0.14 ± 0.10 [b]	0.65 ± 0.10 [a]	0.54 ± 0.15 [a]	0.47 ± 0.07 [a]
	Less Labile Carbon		Non-Labile Carbon	
Rubber	0.16 ± 0.05 [a]	0.58 ± 0.17 [ab]	0.72 ± 0.16 [a]	0.58 ± 0.17 [a]
Oil Palm	0.09 ± 0.03 [a]	0.15 ± 0.06 [a]	0.37 ± 0.12 [a]	0.16 ± 0.09 [a]
Areca Nut	0.05 ± 0.03 [a]	0.11 ± 0.04 [b]	0.64 ± 0.13 [a]	0.28 ± 0.12 [a]
Teak	0.14 ± 0.04 [a]	0.14 ± 0.10 [a]	0.56 ± 0.17 [a]	0.51 ± 0.15 [a]

± indicates standard error of mean. Values in same column followed by different letters are significantly different ($p<0.05$)

Table 5.5: SOC Concentration (%) of varying lability at selected plantations (0-40cm soil depth) in Aizawl, Mizoram.

Plantation	Very labile carbon	Labile carbon	Less Labile Carbon	Non-Labile Carbon	Active Pool	Passive Pool
Rubber	0.66 ± 0.72 [a]	0.57 ±0.19 [a]	0.37 ± 0.11 [ab]	0.65 ± 0.11 [a]	1.22 ± 0.17 [a]	1.02 ± 0.19 [ab]
Oil Palm	0.91 ± 0.63 [a]	0.54 ± 0.06 [a]	0.09 ± 0.03 [a]	0.36 ± 0.08 [a]	1.45 ± 0.09 [a]	0.39 ± 0.08 [b]
Areca Nut	1.29 ± 0.63 [b]	0.47 ± 0.05 [a]	0.12 ± 0.03 [b]	0.47 ± 0.11 [a]	1.72 ± 0.11 [a]	0.55 ± 0.10 [a]
Teak	0.89 ± 0.11 [a]	0.51 ± 0.08 [a]	0.14 ± 0.05 [a]	0.53 ± 0.11 [a]	1.4 ± 0.07 [a]	0.67 ± 0.09 [a]

± indicates standard error of mean. Values in same column followed by different letters are significantly different ($p<0.05$)

5.5. Discussion

5.5.1. Physico-chemical properties of soil

The soil physical and chemical properties are governed by various factors at a point of time and the results of the study revealed that these properties have significant differences among the selected plantations. pH has an important role in the relation between soil and plants since it controls the biochemical process of the soil. This in turn determined the soil‘s fertility and non-fertility. The soil pH was all found to be slightly acidic, and it increased with the increase in soil depth in all the plantations. This trend contrasted with other studies done in monoculture and agricultural land use (Sharmal et al., 2002; Yang et al., 2020; Dhaliwal et al., 2021). In their studies, the reasons for the decrease in pH with increase soil depth was due to the decrease in concentration of exchangeable ions as well as application of lime in the fields to increase the soil pH. However, in our study, we found no correlation between the pH and the micronutrients although the depth of the soil had a negative relationship with the micronutrients. The micronutrients (available nitrogen, potassium, magnesium and calcium) as observed in the results of our study, decreased with the increasing soil depth in all the selected plantations. This decrease of micronutrients with the increasing soil depth could be credited to decrease in organic matter content with the increase in soil depth (Chima et al., 2014). The partially decomposed organic materials on the soil surface may also provide a suitable environment for the concentration of micronutrients such as Zn, Fe and Mn on the surface soil (Follet, 1969). A strong correlation between organic matter and extractable Zn, Cu, Mn and Fe were reported by Sharmal et al., (2002) and this could explain the reason for decrease of micronutrients with the increasing soil depths in all the plantations. The decrease in concentration of available nitrogen with increasing soil depth could be due to the concentration of available nitrogen influenced by organic matter (Chima et al., 2014). The contents of carbon and nitrogen decline could be credited to the lowering of net primary production, litter and fine root biomass in the plantations (Liao et al., 2012). The increase in soil pH with increasing soil depth could be due to the alteration in litter quality, root exudates and the trees increased their uptake of cations (Gunina et al., 2017). Another factor could be the presence of organic matter in soil and other elements present in the plantation soil (Kooch et al., 2020). The aggregation and decomposition of organic matter is the main cause for soil acidification. Humic substances are produced by the decomposition of plant residues in soils, and they release hydrogen ions which are pH dependent (Ampong et al., 2022). Soil pH can also be influenced by low moisture content since there could be insufficient soil moisture for limestone present in the soil to react (Pandey & Pandey, 2010).

Moisture content showed a significant increase with soil depth in all the plantations. The lower moisture content in the upper layer of the soil was most likely influenced by the soil organic matter and soil texture (Harianti et al., 2021). The moisture content of the was highest in rubber plantation which was nearly 30% while it was lowest in teak plantation at almost 16%. The thick litter layer on the floor of the plantation and the shade provided by the mature rubber trees may retain moisture in the soil (Wang et al., 2011; Das et al., 2021), causing the high moisture content in rubber plantation. Teak is vulnerable to poor drainage conditions, and it restricts the development of roots as well as has an impact on the growth of the trees (Choudhari & Prasad, 2018), hence the low moisture content in soil compared to other plantations. It has been observed that there is a direct correlation between the growth of teak and other soil parameters such as pH, calcium, magnesium but no significant correlation was observed between the soil organic matter content and teak growth (Choudhari & Prasad, 2018).

Soil bulk density is an indicator of the compactness of the soil, and it helps in determining the infiltration, soil water porosity, available water capacity, soil microorganism activity, root proliferation and nutrient availability (Indoria et al., 2020; Frene et al., 2024). The bulk density increased with the soil profile in all the plantations, however, it is widely known that bulk density tends to increase with depth as the sub-surface layers have reduced organic matter, aggregation and root penetration when compared to the surface layers as well as less pore space in the soil (Al-Shammary et al., 2018). Oil palm plantation showed lower bulk density compared to the other selected plantations, and a similar pattern was observed by Shrivastava et al. (2021), and their low bulk density was attributed to their fibrous and bulky biomasses. Das et al. (2021) reported the bulk density of rubber decreased from 5-20 years old and gradually increased with the age of the rubber plantation. Yet, our results contrasted with Yasin et al. (2010) and Choudhary et al. (2016) as they observed decrease in bulk density of their rubber plantations with the increase in soil depth. The decrease in bulk density could be due to destruction of soil structure by land preparation. One of the main reasons for decrease in soil nutrients and variation in microorganism‘s diversity in rubber plantation was extraction of latex from the trees and weed control measures used in these plantations (Sungthongw & Taweekij, 2019).

5.5.2. SOC Concentration of SOC Stock

SOC stock increased with soil depth in all plantations except rubber plantation. The SOC concentration in oil palm plantation tend to gradually decrease at the initial stage and increase after bearing of fruits; this increase in SOC stock of oil palm plantation may be the result of application of fertilizers and other management practices (Singh & Sahoo, 2018a). The decrease in SOC stock within the soil depth could be due to the differences in the annual leaf litter decomposition of the plantation floor, this may have assisted in build-up organic matter (Das et al., 2021). In our study, we found that all the plantations apart from oil palm have a significant variation with the SOC stock. There was no trend observed in the SOC concentration and SOC stock in our study areas. Bulk density is often negatively related with organic carbon, hence the increase in bulk density with soil depth and the decrease in SOC in all the plantations except in oil palm can be justified. The tendency of bulk density to increase with the increase in soil depth can be attributed to the compaction of soil and the presence of organic carbon or organic matter in soil can make the soil porous and loose (Selassie & Ayanna, 2013). Due to the presence of more organic matter from trees, SOC tend to decrease with the soil depth since the topsoil contain the maximum amount of SOC. The decrease in SOC of our plantations can be justified as similar studies conducted by Soleimani et al. (2019) and Lepcha & Devi, (2020) and the reason for this decrease can be attributed to the trees regularly adding litter in the upper layer of the soil and accelerate the root turnover, which enhanced the SOC (Yang et al., 2020). In plantation and agriculture, there can be lower SOC content due to lack of input of organic matter and many soil disturbances thus resulting in high carbon mineralization (Singh et al., 2018a). SOC content can also be reduced due to biomass removal during harvesting and regular tillage ends up breaking in the soil macro aggregates (Schroeder, 1994).

The loss of SOC in the soil layers of rubber plantation may have been due to vegetation cover loss (Brahma et al., 2018). The age of rubber plantations may have a role in their SOC content since younger rubber plantation had lower SOC stock compared to rubber plantation over the age of 15 years (Choudhary et al., 2016; Das et al., 2022). They believed that the lower canopy density of younger rubber plantations could lead to vulnerability of soil surface to sunlight, thus leading to loss of SOC on the upper layers. SOC of teak soil plantations tend to decrease gradually with increase of soil depth, which is an indicator that penetration of organic carbon is slow in the soil (Usuga et al., 2010). A study done in Myanmar (Suzuki et al., 2007) also showed a similar trend with our study in teak plantations and they credited the decrease in SOC stock to be caused by poor leaching of nutrients and lesser intake of the trees for their growth. Areca plantation‘s SOC content also decreased with the soil depth. It may be caused by input of higher organic matter and increase of microbial activities in the upper layer of the soil (Lepcha & Devi, 2020).

In our study, only oil palm showed a positive relation between their bulk density and SOC concentration along with SOC stock as both increase with depth. In Malaysia, a similar pattern where SOC stocks were lower in the topsoil of oil palm plantation were also seen (Rahman et al., 2018). The increase rate in mineralisation accompanied by disturbance of soil due to clearing of land, repeated removal of crop residues and soil erosion were the justification for this attribute (Gatkal et al., 2024). The shallow root system of the oil palm and the density of soil during the establishment period of the plantations caused a hindrance to transportation of soil organic matter into further layers of the soil (Debasish-Saha et al., 2014). SOC concentration and stock decrease with soil depth, can negatively affect soil health and productivity, thus, emphasis on maintaining organic matter in the upper soil layers to enhance soil quality and long-term productivity (Hrahsel & Sahoo, 2024).

5.5.3.Relationship between soil parameters and carbon fractions in SOC

In our study, the relationship between the various soil parameters and soil depth revealed a positive relationship between the soil depth and bulk density. However, total carbon, available nitrogen, potassium, magnesium and calcium exhibited a negative relationship. Hence, due to this relationship, bulk density increased with the depth of the soil in our study while the other soil parameters decreased with the increasing soil depth. Choudhari & Prasad (2018) observed a direct relation between growth of the trees and the soil parameters (pH, calcium, magnesium) but no relation between the soil organic matter and the growth of trees. This aligned with our study which shows only a positive correlation between bulk density and SOC stock. Chima et al (2014) credited the decrease of micronutrients and available nitrogen to decrease in organic carbon which corresponds to our study, where both the SOC (except for oil palm) and the other soil parameters decreased with depth of the soil. Sharmal et al. (2002) also noticed a strong relation between organic matter and zinc, copper, magnesium and iron. Liao et al (2012) believed that the contents of carbon and nitrogen may decline due to lower net primary productivity, litter and fine root biomass in the plantations compared to natural forests. A negative relationship was observed by Mahmud et al. (2018) between the soil depth and nitrogen present in the soil of monoculture plantations. They also found that potassium was negatively linked with the soil depth which had a similar result from our study.

5.5.4. Active and passive carbon pools

Active pools are more easily influenced by management practices than passive pool and they can be used as early indicators of soil quality (Sahoo et al., 2019). The significant differences in TOC content between the plantations indicated how SOC was influenced by nature of crop and its management practices. Loss of SOC content in the topsoil affected the SOC content in the sub-soil. Decrease of SOC content with increasing soil depth can be due to absence of perennial trees and higher intensity of soil erosion. The inputs of leaf litter, root biomass and its recalcitrant character can prevent microbial decomposition could influence the SOC content in our study (Nath et al., 2018b). Litter input is a significant pathway for dead organic matter and nutrients that were held by the plants to return to the soil. The lesser TOC content in our study indicated that depletion of SOC stock by these plantations had occurred due to alterations of management of practices as well as the plant species (Wang et al., 2014a). Numerous studies have illustrated that management practices play a crucial role in influencing the carbon contents in the biomass and soils (Peichl et al., 2006). The SOC concentration relies on the productivity of the plants since its management leads to the organic matter input of the active soi carbon fraction (Bruun et al., 2015). The consecutive inputs of easily decomposable leaf litter throughout the year may have resulted in the value of labile carbon in our study. Absence of canopy covers increase the rate of mineralization due to the direct exposure of solar radiations and the steep slope nature of the state with heavy rainfall leading to more incidence of soil erosion ultimately leads to loss of SOC of the surface soils (Kenye et al., 2019). Root exudates are known as eminent ‗labile' sources of soil carbon that can prime microbial activity and recent investigations indicated that the stability of labile carbon inputs in soil mostly depends upon the physical, chemical, and biological properties of the surroundings (Conteh et al., 1997; Panchal et al., 2022). Increase in litter fall also may increase the passive carbon pool due to the organic pool being more stable. Land use and management influenced the active and passive carbon pool in both the soil depth, thus, poorly managed plantations may have a negative effect on the carbon sequestration (Sahoo et al., 2019).

5.6. Conclusion

Our findings indicated that SOC concentration and stock decreased with increase soil depth, and this can negatively affect soil health and productivity. This suggested that land managers should focus on maintaining organic matter in the upper soil layers to enhance soil quality and long-term productivity. The study also highlighted that different types of plantations have varying SOC stocks. For instance, teak plantations showed the highest SOC stock, while areca nut plantations had the lowest. This information can provide farmers and land planners in selecting appropriate tree species for plantations that optimize carbon storage and improve soil fertility. Increasing the addition of litter through plant residues can also aid in maintaining SOC stocks. The research further indicated that the conversion of natural forests to plantations can disrupt soil structure and lead to SOC loss. Thus, there is need for careful planning and management of land use changes to minimize negative impacts on soil carbon stocks and overall ecosystem health. Proper management of SOC not only supports environmental goals but also offers economic benefits. By enhancing soil fertility and productivity, farmers can achieve better yields, which can improve their livelihoods while contributing to sustainable land use practices.

CHAPTER VI- EVALUATION OF NET ECOSYSTEM PRODUCTIVITY IN THE SELECTED PLANTATIONS

6.1. Introduction

Anthropogenic activities and deforestation have increased the carbon emissions in the last two centuries and this has caused an increase on the atmospheric temperature (Bode & Jung, 2005). The accumulation of carbon in the atmosphere has also caused global warming and climate change. The carbon balance of terrestrial ecosystems can be represented by net ecosystem productivity (NEP) and net ecosystem carbon exchange (NEE). Net ecosystem productivity (NEP) is the net change in the ecosystem in carbon storage which involves the fluxes from vegetation, detritus and soil mineral (Ahlström et al., 2015). It quantifies both the accumulation and loss of carbon since it represents the annual change in carbon stored in the ecosystem. NEP is the difference between the gross primary productivity (GPP) and heterotrophic respiration (RH). Gross primary productivity (GPP) is the total amount of organic matter that plants produce through photosynthesis at a given period of time, and it represents the total energy captured by plants from sunlight. GPP plays a crucial role in ecological studies and helps in understanding the energy flow through the ecosystems (Kumar et al., 2021; D. Yang et al., 2021). In context of research work, GPP is a key parameter used to study the overall assessment of productivity of ecosystems, impact of environmental factors on plant growth and contribution of different plant species to the energy budget of the ecosystem. It is important in understanding the ecosystem dynamics, carbon cycling and potential effects of climate change in vegetation productivity (Yan et al., 2023). The balance between GPP and RH can determine the net ecosystem exchange (NEE) and it can ascertain whether it will be a carbon source (positive) or a sink (negative). It is an essential metric in understanding the carbon cycle and the role of ecosystems in sequestering or releasing carbon dioxide. It is frequently expressed in terms of carbon and considers both the primary production by plants and carbon loss through plant respiration. Researchers on NEP can used to assess the carbon dynamics of various ecosystems like forests, grasslands, wetlands and even oceans. Understanding and monitoring of NEP is crucial for studying the impact of climate change, land-use changes and other factors on the overall carbon balance of different ecosystems.

Proper management for restoration of carbon through monoculture plantation varies substantially by the genus of tree and plant functional type. In northeast India, degraded lands can be restored through rubber plantation and agroforestry since they can enhance ecosystem carbon sequestration and reduce carbon dioxide emission from changes in land use (Brahma et al. 2018). Plantations in northeast India can store carbon and help in mitigation of climate change (Mishra et al., 2021). Mature rubber plantations contribute to soil rehabilitation by increasing aggregate stability, recalcitrant carbon pool and soil organic carbon stock and minimizing soil degradation (Kurmi et al., 2020). In rubber and oil palm plantations, extended rotation can lead to higher carbon sequestration (Egbe, 2012).

Soil organic carbon (SOC) has an important role in climate change mitigation as it acts as a significant carbon sink, sequestering carbon from the atmosphere and reducing greenhouse gas emissions. SOC sequestration can be achieved through various means, such as the use of organic soil modifications like manure and mulch as these enhance soil health and increase carbon storage (Holka et al., 2022). Mountain ecosystems, due to their lower temperatures and higher precipitation, have a high potential for SOC storage (Ortiz et al., 2023). Yet, the effectiveness of SOC sequestration strategies depends on various factors, including soil type, land cover, and management practices. The impact of SOC on NEP in plantation ecosystems is multifaceted, influencing both carbon storage and ecosystem health. SOC plays a critical role in enhancing soil quality, which in turn supports plant productivity and overall ecosystem functions. Increased SOC levels correlate with higher net primary production (NPP), as SOC serves as a reservoir for nutrients essential for plant development (Borah & Parmar, 2024). SOC levels significantly reduced with litter and root removal, indicating the importance of organic inputs for maintaining SOC and, consequently, ecosystem productivity (Hao et al., 2024). Climate change accelerates SOC decomposition, hence reducing its availability and impacting NEP negatively (Borah & Parmar, 2024). The interaction of carbon and nitrogen inputs can also influence SOC dynamics, affecting microbial activity and soil respiration, which are crucial for maintaining NEP (Meena et al., 2024). Furthermore, while SOC is vital for enhancing NEP, excessive reliance on external inputs without sustainable practices may lead to soil degradation and reduced long-term productivity. Thus, a balanced approach is necessary to maintain SOC levels and ecosystem health.

NEP in plantation ecosystems is a critical measure of carbon balance, reflecting the difference between carbon uptake through photosynthesis and carbon release via respiration. Numerous studies have explored NEP in different plantation types, employing diverse methodologies to estimate and model these processes (He et al., 2012; Poungparn et al., 2012; Zheng et al., 2019; Zhang et al., 2024) Their findings highlight the complexity and variability of NEP across different plantation ecosystems. Although these studies provide valuable insights into NEP in plantation ecosystems, they also emphasize the challenges in accurately modelling and measuring these processes. Factors such as model complexity, data resolution, and environmental variability can significantly impact NEP estimations (Yan et al., 2023). Additionally, the role of plantations in carbon sequestration and their potential to offset carbon emissions from land-use changes are crucial considerations for sustainable forest management and climate change mitigation strategies.

6.2. Methodology

6.2.1. Conceptual Framework for estimation of net ecosystem productivity (NEP) in selected plantations

The calculations for all the other variables were made in the following:

- Aboveground (AG) litterfall = Litter production (AG) + Decay (AG)
- Belowground (BG) litterfall = Litter production (BG) + Decay (BG)
- Mortality (AG)= Dead Biomass (AG) + Mortality (AG)
- Mortality (BG)= Dead Biomass (BG)
- NPP (AG)= AG Live Biomass + Mortality (AG)
- NPP (BG)= BG Live Biomass + Mortality (BG)
- Heterotrophic respiration (Rh)= Decay (AG+BG) – SOC

- Autotrophic respiration (Ra) = Rt-Rh
- NEP = NPP(AG+BG)- (Harvested Biomass + Burnt Biomass +Rh)

Decay was calculated using Olson, (1963) differential equation for organic matter cycling in terrestrial ecosystems.

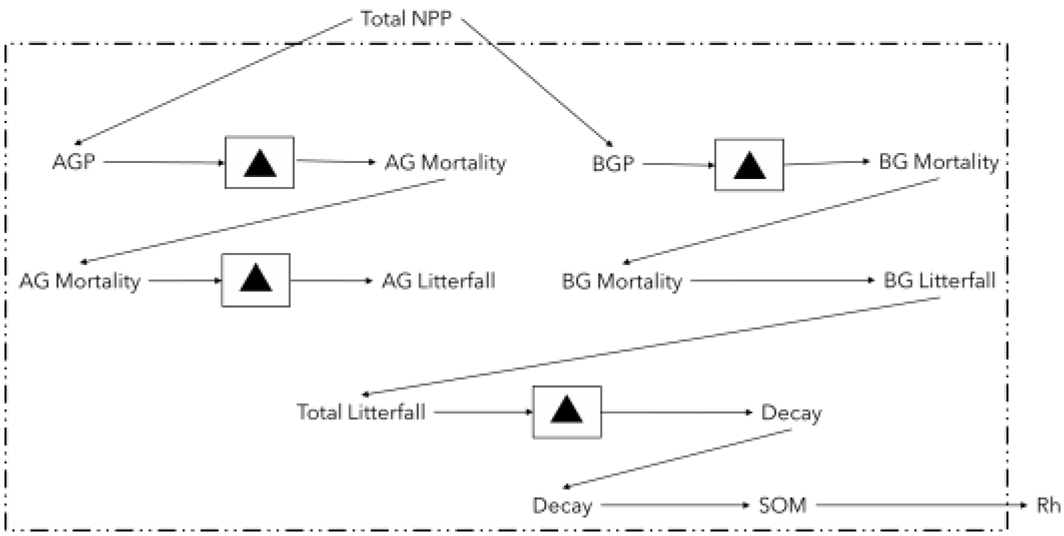


Figure 6.1: Conceptual framework for estimation of NEP in selected study sites.

6.2.2. Quantifying biomass production

For biomass sampling, the non-destructive method was employed to estimate the aboveground biomass of tree species. Four quadrats (15 m x 15 m) were placed randomly in the site for sampling of trees. All trees exceeding 30 cm girth over bark at breast height (1.37 m) were identified and tagged. The girth was measured using a metal tape and height was estimated using pole method during December 2020-March 2021 and December 2023-March 2024. Since it was a monoculture plantation with little to no other trees, there were hardly any trees to be identified. In each monthly sampling date, all four quadrats were sampled. Above ground parts were weighed in the field and sub-samples were subsequently oven-dried at 70ºC to constant weight. Soil samples were collected from quadrats used for above ground biomass sampling. Thus, four soil samples were collected from four quadrats to be used for above ground biomass data collection. After the collection of soil cores, below ground parts were brought to the laboratory and washed carefully to remove the soil. Identification of below ground living and non-living parts were carried out visually (Baillie et al., 1990). The live roots and rhizomes are hyaline while the dead parts are brown or black in colour. The sub-samples were then oven-dried at 70ºC to constant weight so as to obtain live and dead below ground biomass. Aboveground trees and shrubs were calculated using specific allometric equations designed for the specific trees.

The following biomass equations were used to estimate the aboveground biomass (AGB):

Sl No	Species	Biomass Equation	References
1	*Hevea brasiliensis* Müll.Arg.	Biomass= -(exp(1-3.31+0.95(lnD^{2}H)) x 1.02	Brahma et al. (2018)
2	*Elaesis guineensis* Jacq.	Biomass = 71.797 x H – 7.0872	Asari et al. (2013)
3	*Areca catechu* L.	Biomass = exp(-1.853+0.728(lnD^{2}H))	Das et al. (2021)
4	*Tectona grandis* L.f	Biomass = 0.4989D^2-0.202D-21.971	Jha (2015)

6.2.3. Quantifying aboveground litter production and decay

In order to quantify aboveground litter production, surface litter (Litter AG) (dead leaf and branch) and standing litter were studied at monthly interval by randomly laying four litter traps (1 m x 1m) in each 0.1 ha plot. A minimum distance of 1 m from the tree bole in litter trap laying was followed to get the best observations. Dead leaves and branches present in the litter trap were collected and air-dried. Fresh weight and dry weight ratios were estimated from sub-samples of the litter. Samples of air-dried aboveground litter weighing 10 g were placed in 10 cm x 10 cm nylon litter bags (1 mm mesh size). Sixty such bags were prepared for each of aboveground parts totaling 240 bags. Litterbag technique was used for studying litter decomposition. Five litter bags were taken out at monthly interval until 95% of decomposition was obtained. The residual material from each bag was oven-dried at 70ºC until constant weight. Mass monthly loss (gram/month) were determined from the difference between mass of litter remaining in the litter bags in a particular month and the mass of litter in the litter bags of the previous month.

6.2.4. Quantifying belowground litter production and decay

To quantify belowground litter production, dead fine roots or the belowground litter production in the present study was done through the sequential core method. For root (Litterfall BG), sampling was done with soil cores (diameter 5.5 cm) up to 20 cm soil depth at quarterly intervals with 10 replicates from the representative plots. Thus, ten soil samples for belowground litter production under a single plantation were collected and brought back to the laboratory in zip-lock bags. In the laboratory, roots were cleaned from soil and organic residues by a gentle stream of water over a sieve. Roots less than or equal to 2 mm diameter were separated manually. Live and dead roots were carefully separated soon after removing the roots of other plants.

6.2.5. Fine root biomass production

For fine root production, five random plots with 10 m x 10 m were laid within each of the representative plots. Soil samples were collected up to a depth of 20 cm with soil core. After removing live fine roots from the soil, the rootless soil samples were placed in litter bags and inserted in the soil pit from where the soil samples were collected. Samples were collected from each site and taken to the laboratory for further analysis. In the laboratory, soil samples were soaked overnight to clean the roots from soil and organic residues. For estimating the fine root biomass, the dry weight of the fine roots was taken after drying at 70º C for 72 hrs.

6.2.6. Fine root decomposition

Fine root decomposition rate under forest stands was determined through mesh bag technique (McClaugherty et al., 1984; Fahey et al., 1988). Dead fine roots were collected from the top-soil layer from the forest. The washed roots were dried up at 65ºC for 48 hours (Jamro et al., 2015). Around 50 mesh bags of 5 cm x 5 cm size and 1 mm mesh size with 3 g of root material were kept in the previously prepared plots. Four bags were extracted at monthly intervals and taken to the laboratory. During the laboratory analysis (after collecting the mesh bags from the field), the residual roots were carefully removed from the bag and washed gently over the mesh to remove the adherent soils. After washing the residual roots were dried at 65ºC for 48 hours and the dry weight of each sample was measured.

6.2.7. Quantifying soil organic carbon

Soil samples from 0-20 cm depth were collected from four different random plots from each selected plantation. Soil bulk density was determined using the soil corer method and the soil sampled were air dried and sieved with a 2mm sieve. Soil organic carbon was determined by Walkley & Black (1934) rapid titration method and the SOC stock was determined by considering SOC concentration, bulk density (corrected for coarse fraction) and soil depth using the following equation:

$$\text{SOC stock (Mg ha}^{-1}) = [\text{SOC\%} \times \text{corrected BD (Mg m}^{-3}) \times \text{T (m)} \times 10^4 (\text{m}^2\ \text{ha}^{-1})]/100$$

6.2.8. Quantifying soil respiration

Soil respiration was measured using Q-Box SR1LP, which is designed for short-term measurements of soil respiration and water loss in fields. Soil temperature, soil moisture and atmospheric pressure can be measured using this Q-Box (Tomar & Baishya, 2020). The Q-SR1LP measured CO_2 accumulation rates using the Q-S151 CO_2 analyzer to assess soil respiration. By setting the chamber directly on the ground respiration was measured in field applications, enabling many measurements at the same spot. Soil respiration was measured at a quarterly interval during the sampling period.

6.2.9. Mean Residence Time (MRT) for litters

The Mean Residence Time (MRT) of the litters in each site was calculated using the following formula (Giardina & Ryan, 2000).

$$MRT=1/k$$

where, k is the litter decomposition rate constant, which was estimated using the following formula (Wider & Lang, 1982).

$$Mt/M0 = e^{-kt}$$

where M0 is the initial dry mass of the litter, Mt is the remaining dry mass of the litter at t time.

6.3. Statistical Analysis

Analysis of data was performed using Microsoft Excel 2019 (Version: 16.79.2), SPSS (IBM SPSS Statistics 25) and Janmovi (2.3.28). One-way and two-way ANOVA were performed between the different plantations and soil depth along with the various soil parameters. Test of significance was performed using Tukey‘s HSD with $p \leq 0.05$, where p value greater than 0.05 were rejected. SPSS was used for estimating Pearson‘s correlation and analysis of variance.

6.4. Results

Litter production reached its peak during the month of March of the study period for rubber plantation (Figure 6.2), whereas for oil palm it was in the month of April. Areca nut plantation also exhibited its climax during the month of March, although for teak, it was high during the period of January to April with its highest also in the month of March. The mass loss (%) rates in rubber and oil palm plantation were constant during the study period. In areca nut plantation, the mass loss accelerated with the start of the monsoon season and in teak, it accelerated after the month of July, where the rainfall received during this period was the highest. No significant relationship between the litter mass loss was found with rainfall, however, there was a positive correlation between rainfall and mass loss in fine roots (Table 6.1).

Rubber and areca nut plantation had their highest fine root biomass production during the period of January to March while oil palm had the highest during the April to June. Teak, however, had a lower fine root biomass production compared to other plantations and it was observed to be highest in the period of April to June (Figure 6.5). Belowground biomass was classified into live and dead roots and rhizomes. The highest live belowground production was found for rubber during the months of January to March, while in oil palm it peaked during October to December. Areca nut‘s plantation exhibited live belowground biomass production during the period of October to December and teak showed its highest storage in the months of January to March (Figure 6.6). The dead roots and rhizomes for rubber plantation peaked also during the months of January and March, while oil palm‘s dead belowground storage was found to be highest in December and January. Areca nut dead roots and rhizomes biomass production was the largest in January to March and teak also showed its highest during this period.

The decay for both aboveground and belowground was the highest during March for rubber plantation, whereas oil palm‘s decay was in April. Areca nut plantation showed a gradual increase with its peak in July and for teak, it was highest during the month of November (Figure 6.7). The aboveground mortality was highest in rubber plantation in the month of March, while oil palm peaked in April. On the other hand, Areca nut showed a gradual decline with its peak in the month of January and for teak, it was during November that the AG mortality was found to be the highest (Figure 6.8). Belowground mortality was high in all during the sampling period of October to December with oil palm having the highest BG mortality. April to June showed a lower BG mortality and was lowest for oil palm during this period (Figure 6.9). The net primary productivity (NPP) in rubber plantation surpassed the other study sites (Figure 6.10) and it was lowest in areca nut plantation. Soil respiration was highest in all plantation during the rainy season, with teak having the largest soil respiration (Figure 6.11), this corroborate with rainfall pattern during the study period. The net ecosystem production (NEP) was found to be the highest in rubber plantation at 155.4±7 (Mg C/ha/yr) and lowest in areca nut plantation with values of 40.9±3 (Mg C/ha/yr) (Table 6.2)

Figure 6.2: Litter production vs. Mass loss in selected plantations in Mizoram.

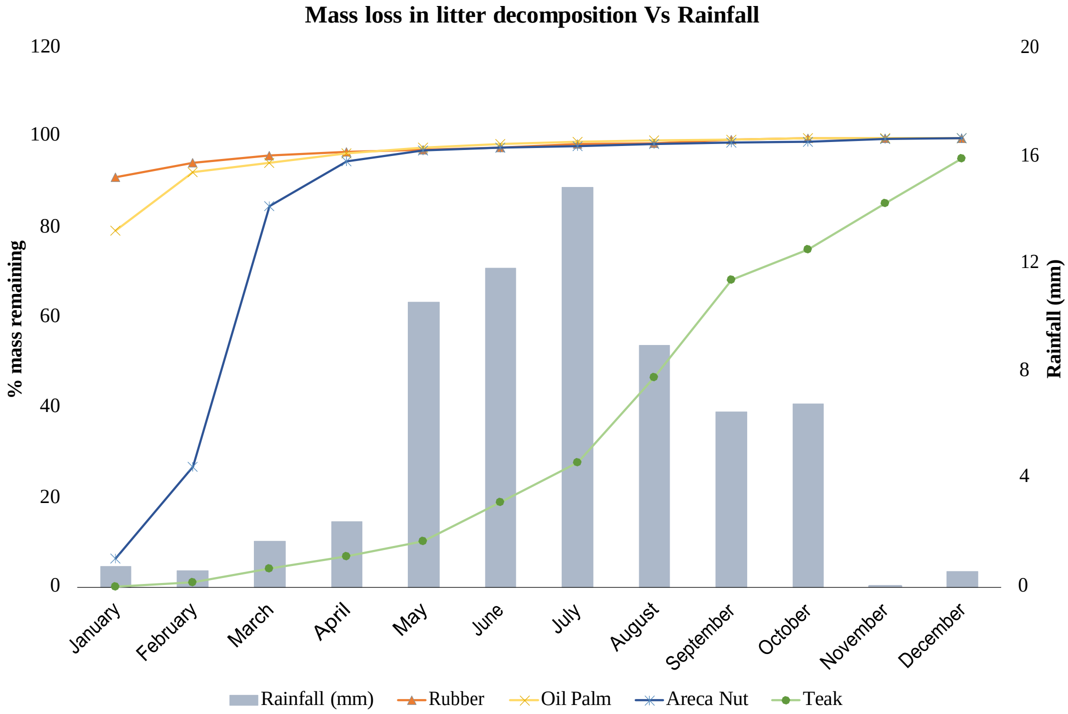


Figure 6.3: Mass Loss in Litter Decomposition vs. Rainfall during sampling period of selected plantations in Mizoram.

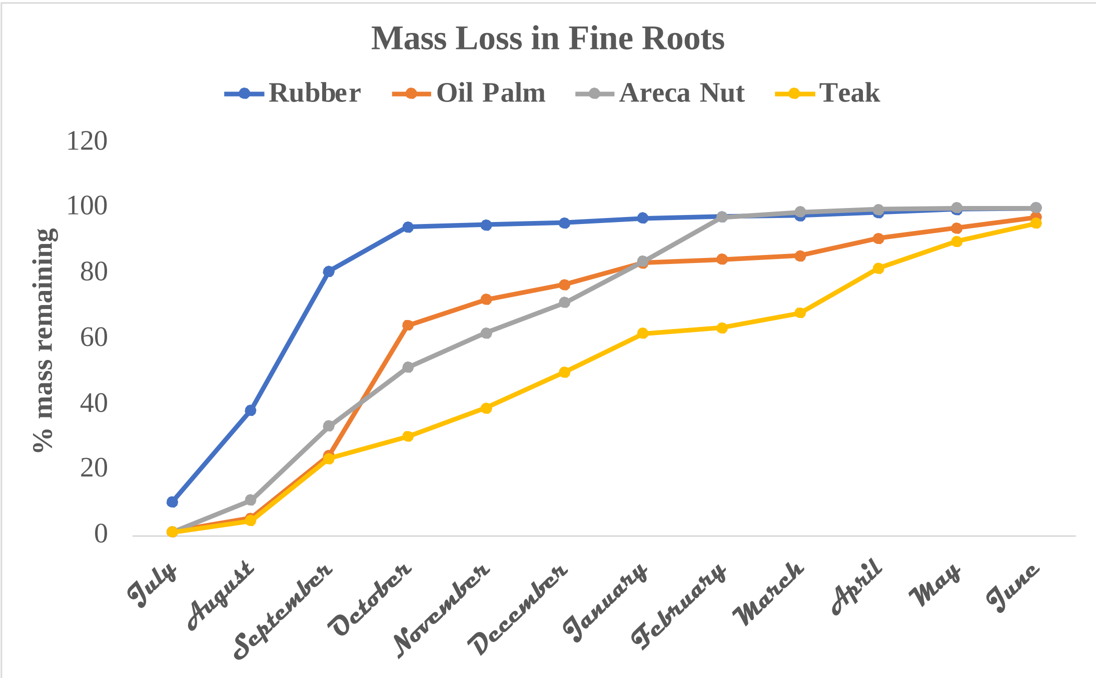


Figure 6.4: Mass loss in fine roots from decomposition in selected plantations in Mizoram.

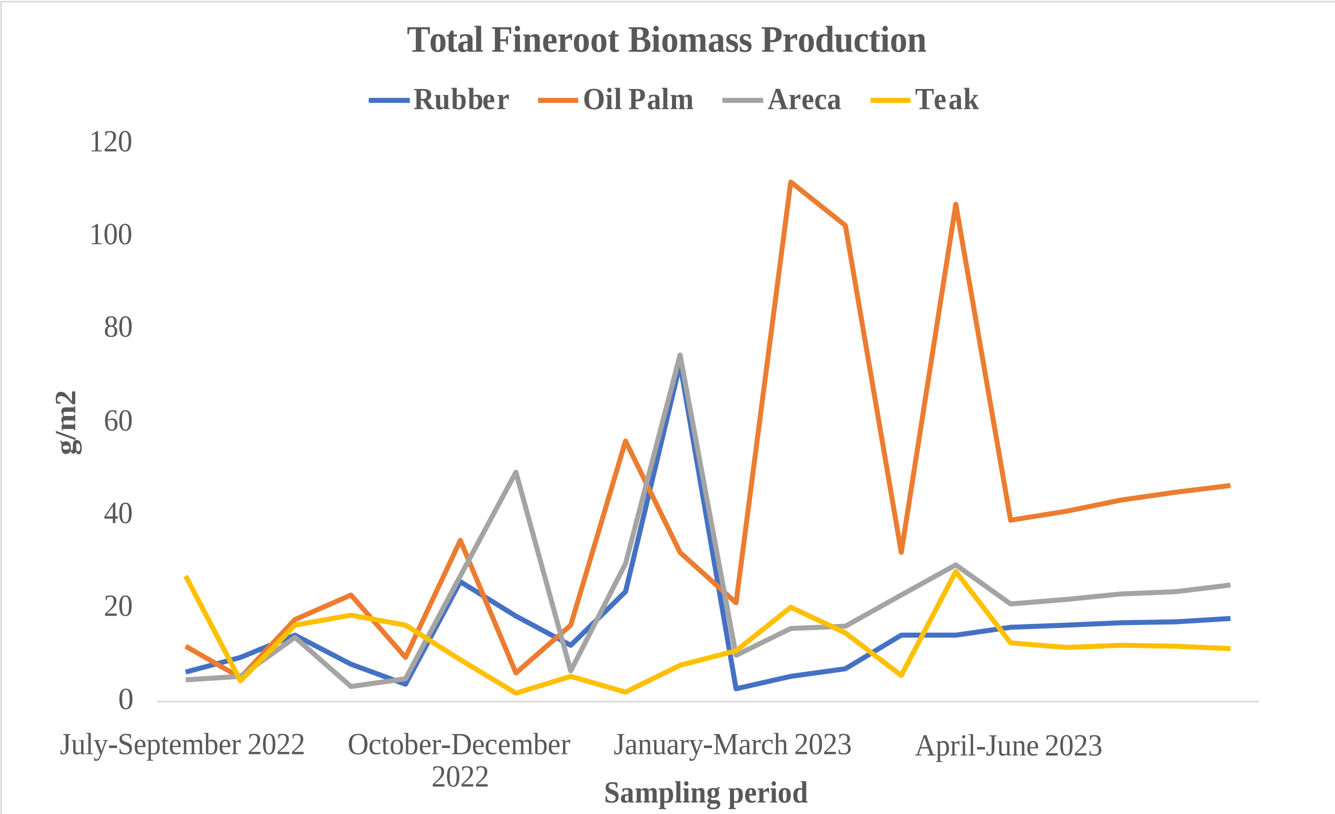


Figure 6.5: Total fine root production during sampling period in selected plantations in Mizoram.

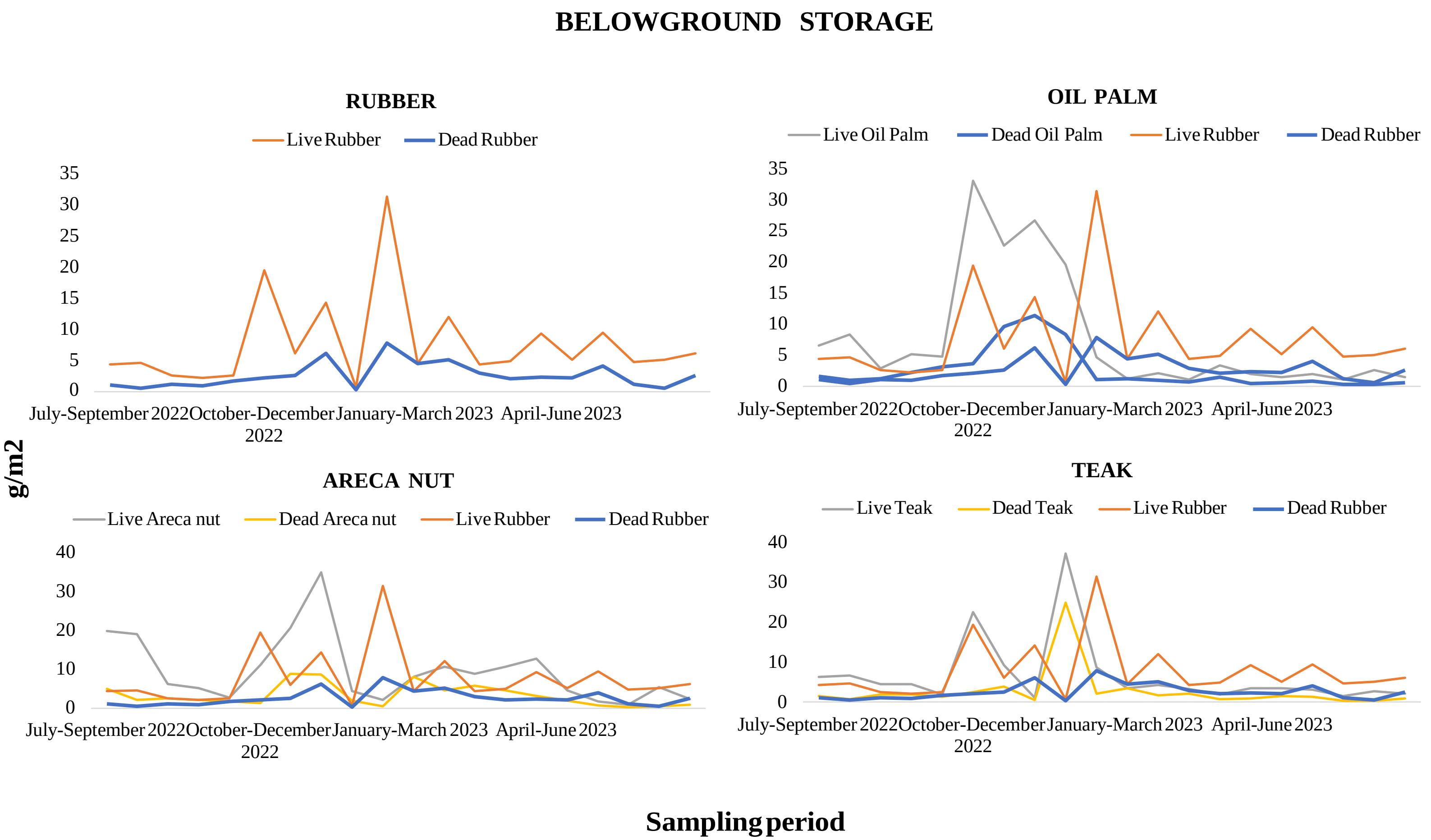


Figure 6.6: Belowground biomass production during sampling period in selected plantations in Mizoram.

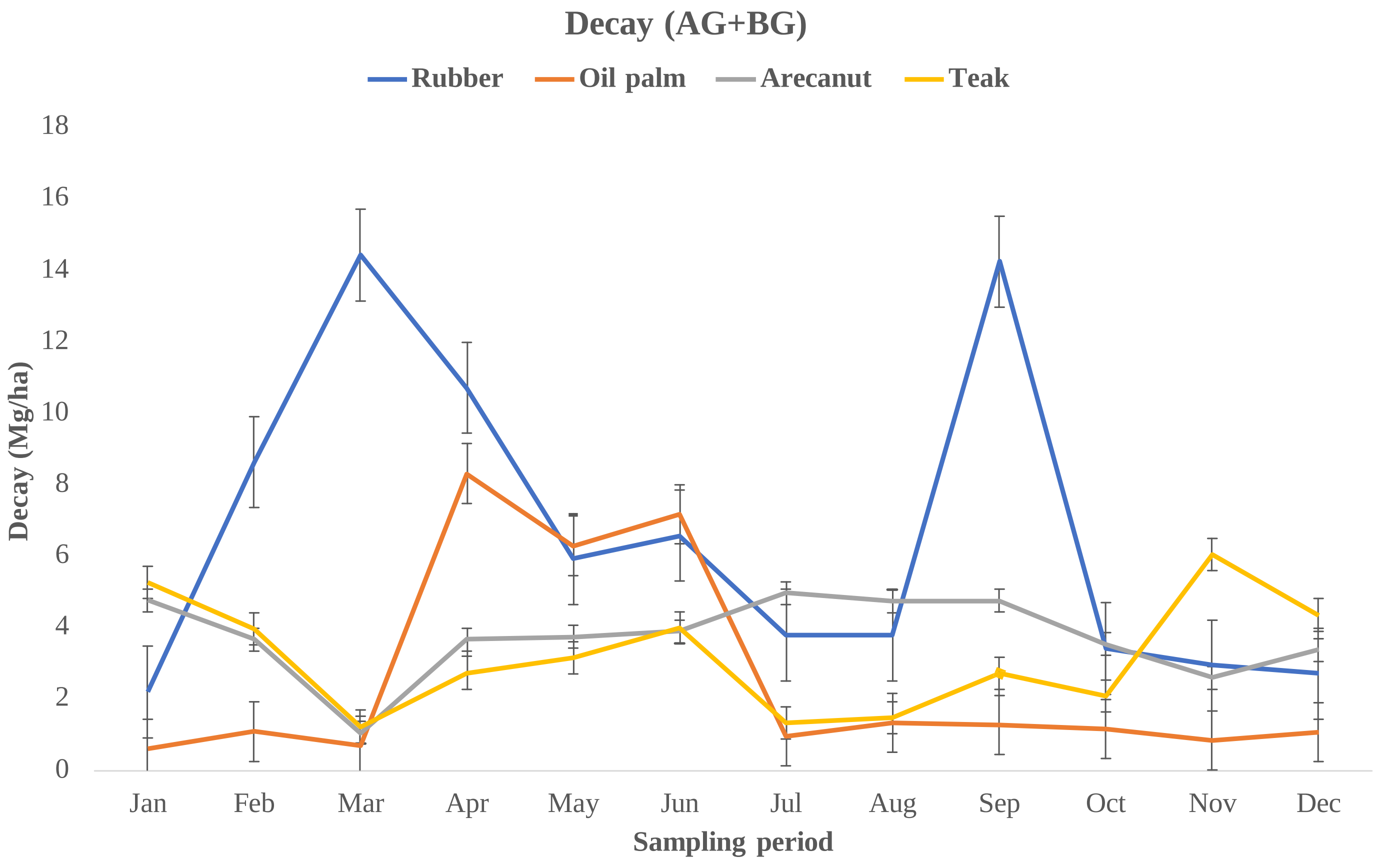


Figure 6.7: Aboveground and belowground decay during sampling period in selected plantations.

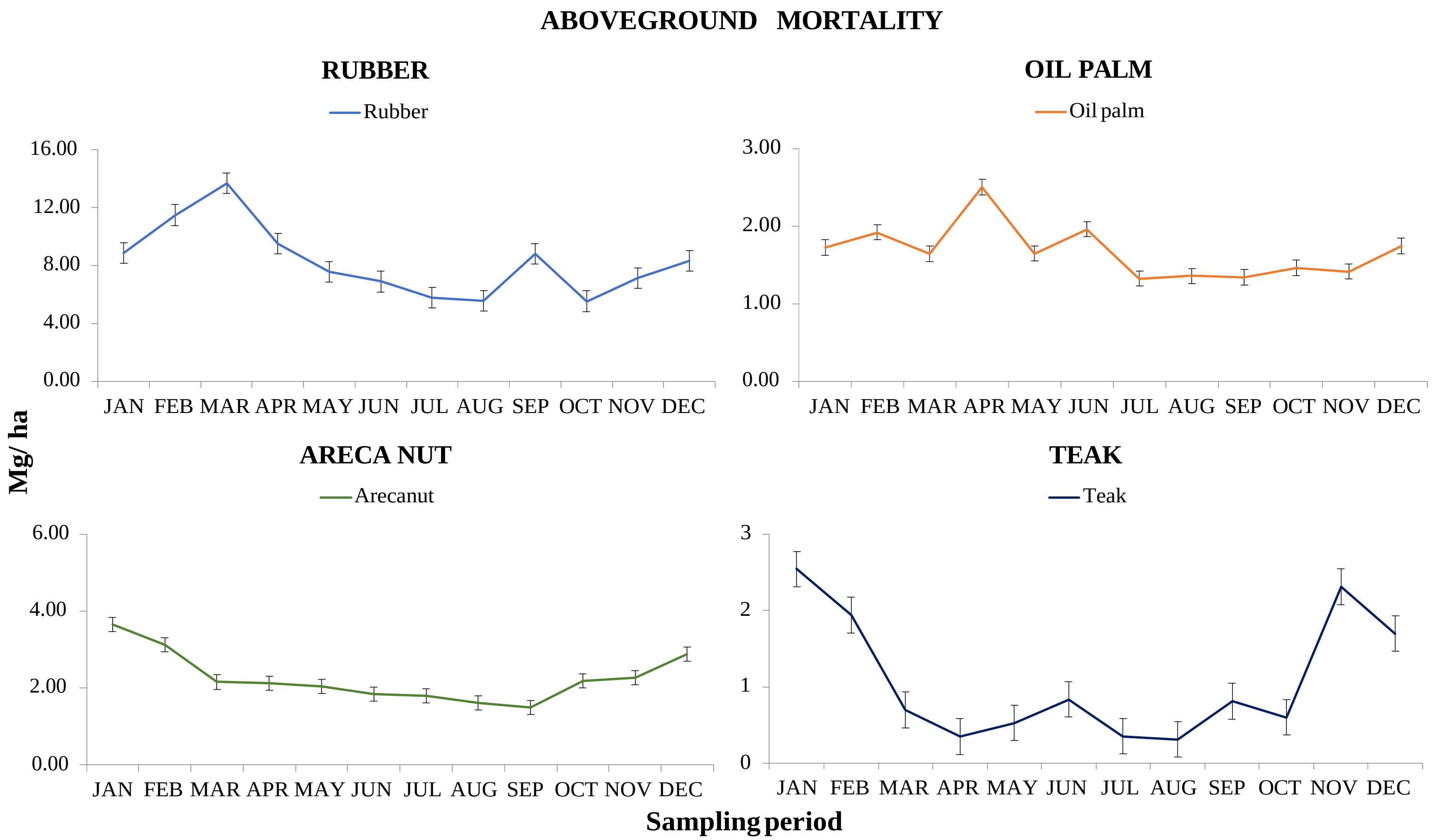


Figure 6.8: Aboveground mortality in selected plantations during sampling period.

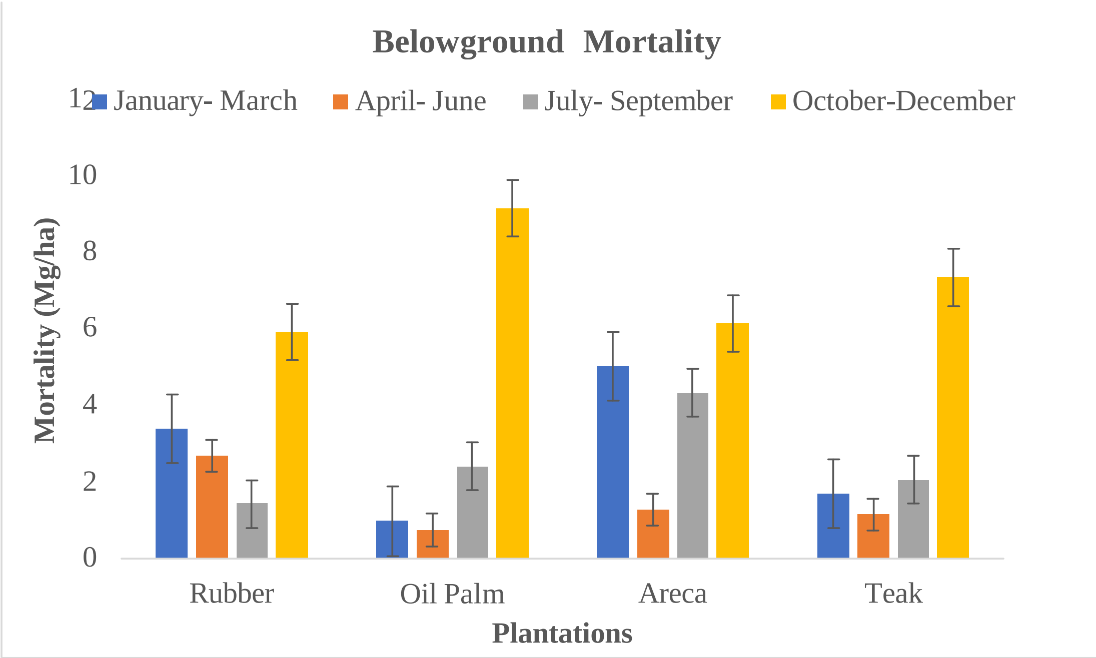


Figure 6.9: Belowground mortality in selected plantations during sampling period.

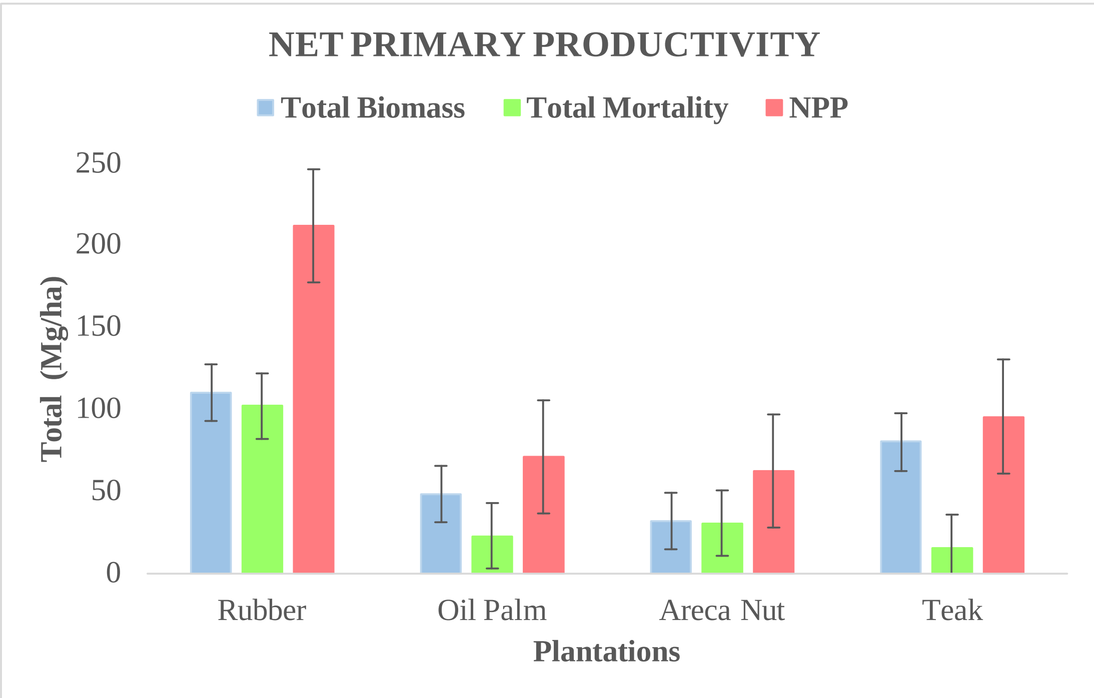


Figure 6.10: Net primary productivity (NPP) of all the selected plantations during the study period at Aizawl, Mizoram.

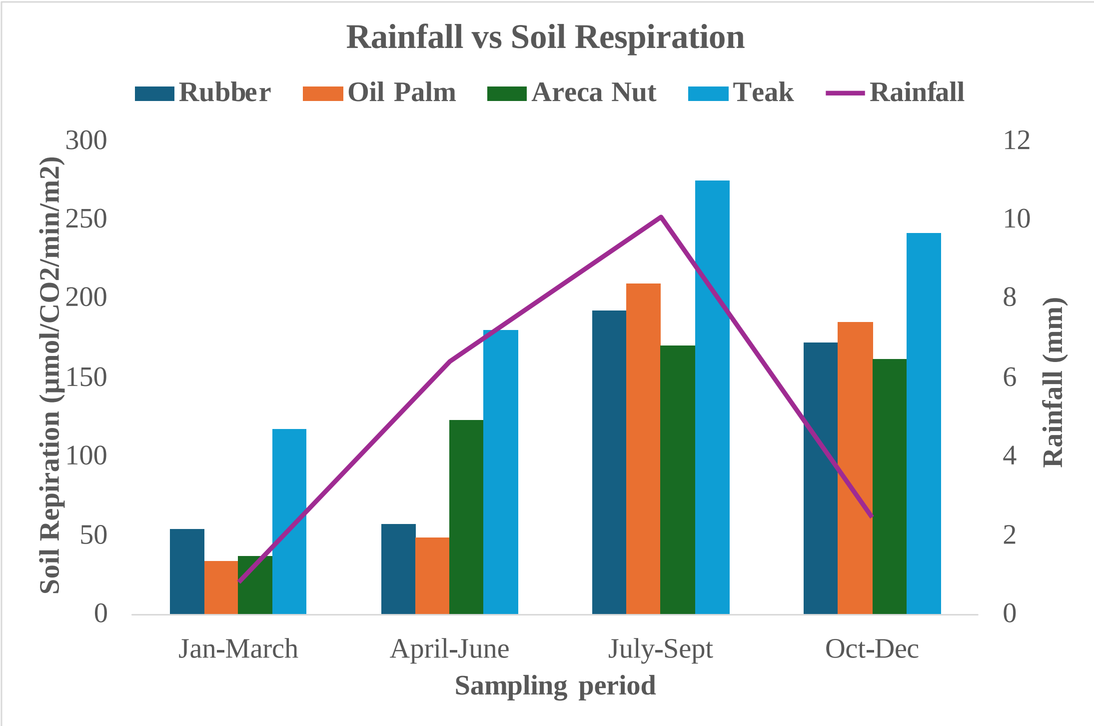


Figure 6.11: Soil respiration vs. rainfall during the study period of selected plantations at Aizawl, Mizoram

Table 6.1: Pearson‘s correlation between rainfall (mm), mass loss in litter and fine roots through decomposition

Correlation	Rainfall (mm)	Litter Mass Loss (%)	Fine roots Mass Loss (%)
Rainfall (mm)	1	0.099	.333*
Litter Mass Loss (%)	0.099	1	.671**
Fine roots Mass Loss (%)	.333*	.671**	1

*Correlation is significant at the 0.05 level (2-tailed).; ** Correlation is significant at the 0.01 level (2-tailed)

Table 6.2: Net Ecosystem Production (NEP) in selected plantations at Aizawl, Mizoram.

Plantation	NPP (Mg C/ha/yr)	Litter (Mg C/ha/yr)	Dead roots (Mg C/ha/yr)	Carbon lost in burning (Mg C/ha/yr)	Rh (Mg C/ha/yr)	NEP (Mg C/ha/yr)
	A	*B*	*C*	*D*	*E*	*[A-(B+C+D+)]*
Rubber	238.1±7.4	49.2±1.2	9.8±0.7	0.7±0.01	23.1±0.7	155.4±7
Oil palm	104.3±7.6	9.6±0.3	9.7±1.5	0.3±0.01	13.7±0.4	71.1±6
Areca nut	75.3±2.1	18.3±0.15	12.3±0.8	0.3±0.01	3.5±0.3	40.9±3
Teak	120.9±1.7	25.5±0.17	8.9±1.1	0.3±0.01	9.9±1.1	76.2±4

± standard error of means

6.5. Discussion

The plantations selected for the present study were monoculture that attained proper management, however, these were not for commercial purposes. The rubber plantation and oil palm plantation, however, were used commercially for a certain period but had ceded by the time it was used for a study site. The biomass of trees did not exhibit increase much due to age of the plantations as they have already reached maturity. After reaching maturity, they tend to stabilise over a period and it gradually increases or decreases (Ming et al., 2014; Du et al., 2015; Justine et al., 2015; He et al., 2021). Litter production reached peak during the month of March and April in all selected plantation sites. This can be attributed to both environmental and anthropogenic factors. The increase in solar radiation and temperature during this period may have a role in litter production (Aquilos et al., 2012) and it is influenced by rainfall as it enhances the organic debris production (Lam & Dudgeon, 1985). Elevation also has a role in litter production as well as timing of the litter fall (Ruiz-Corzo et al., 2023). Litter characteristics also play a crucial part in the relationship between litter mass loss and rainfall. Studies have shown that that rainfall generally enhances litter decomposition and reduced precipitation slows down this process. Higher precipitation levels lead to increased litter mass loss, as observed our study of teak plantation, where litter decomposition rates were significantly faster under surplus rainfall. Reduced rainfall resulted in decrease of nutrient release by the litter and can affect the ecosystem (Qu et al., 2024). The leaves of the plant species presents also have a role in litter mass loss. In rubber plantations, the leaves were less broad and thin compared to the other plantations and thus, the brief rainfall in the start of the sampling period as well as the thickness of the litter layers might have influenced its rapid loss of mass (Xia et al., 2019; Rajão et al., 2023). Furthermore, teak plantation showed a much lesser mass loss due to the thickness of the teak leaves and this can cause the rainfall not to penetrate the soil thus, resulting in reduced decomposition.

The root production tends to peak in warmer months since the air and soil temperatures are higher, promoting growth, its mortality often increases during the autumn/fall and winter period (Ma et al., 2024). Due to the nature of the plantations selected, the belowground biomass and fine root biomass production are relatively lower compared to forests (Lalnunzira et al., 2019) and increasing the availability of nutrients in soils can lead to higher nutrient uptake and better metabolic activity of roots (Świątek & Pietrzykowski, 2021). In some studies, it was seen that roots production increased during the autumn season as they may have more access to nutrients due to higher litter decomposition. This may extent their life span, thus roots that are formed at the end of the growing season may have lower mortality rate with slower growth (Gu et al., 2017). The acidity of soil also influences the root growth by inhibiting the growth and activity of microorganisms (Zhou et al., 2017), therefore, soils with higher pH may stimulate root growth. Magnesium concentration and total carbon content also influence the growth and mortality of fine roots. The reason for rubber and areca nut plantation having their highest fine root biomass production during the period of January to March could be the increase root production in March with the warmer air and soil temperature and rainfall which increases the precipitation. Lower root production in teak may be attributed to its soil‘s low moisture content. In fine roots, the ingrowth corer method was used for fine root biomass production as it was suitable when comparing different sites while sequential coring gives the below ground production. Fine roots found using ingrowth corer method had a longevity of less than three months. Therefore, characteristics of fine root biomass that can grow in a short period of time after installation may vary when compared to those outside the core (Katayama et al., 2019). Different species may show varying belowground biomass production rates.

Dead biomass includes all the dead living thing even the litter that fall from the trees. Live biomass represents the existing, actively growing plant materials and measuring the accumulation gives the NPP. Mortality represents the loss of biomass due to death and it includes the roots, stems and leaves as well as dead branches and standing deadwood. It reduces the total NPP through loss of biomass. The age of the plantation has a role in the NPP as studies conducted in different forests of the United States showed that depending on the forest and species composition, with the increase in age, the NPP also increased (He et al., 2012). High NPP and low heterotrophic respiration are effective carbon sinks and are crucial for mitigating climate change (Poungparn et al., 2012). Soil respiration in monsoon seasons will have higher soil respiration than summer due to the increase rainfall creating favourable conditions for microbial activities and root respiration. The temperature with high moisture gives a suitable condition for higher organic input. Our study also showed that soil respiration peaked during the monsoon season, the high soil respiration in October to December could be the due to precipitation and high rainfall received during the study period.

Some studies that have been conducted showed that dense forests have 30-50 Mg C /ha of NEP, while open forests are lower at 20-25 Mg C/ha (Grant et al., 2010; Poungparn et al., 2012; Zheng et al., 2019; Zhang et al., 2024). NEP is not often comparable as some only calculated the tree biomass, leaves, respiration and often excludes the dead biomass, root biomass. The slopes of the forest also play a role in carbon production as hilly area will have higher production (L. Zhang et al., 2024). Fire affects the ecosystem (Beringer et al., 2007) directly through emissions and indirectly by reducing productivity due to loss of functional leaf area and the carbon costs of rebuilding the canopy. The carbon balance took approximately 70 days to recover after a fire. The NEP values in mangroves, Thailand (Poungparn et al., 2012) ranged from 7.34 to 11.3 Mg C/ha/yr, which is higher than those reported for other upland forests. Schulze et al., (2021) highlighted that current flux measurements often neglect lateral fluxes, especially the export of biomass through harvest. This omission led to an underestimation of carbon losses and hinders the accuracy of carbon budget assessments. Arneth et al. (1998) study on *Pinus* plantation showed that their NPP varied between 8.8 and 10.6 Mg C/ha/year, NEP was between 5.0 and 7.2 Mg C/ha/year. Carbon allocation was mostly to wood, with 47% to stems and 27% to coarse roots. Karmacharya & Singh, (1992) found that the NEP for teak is 25.6 Mg C/ha/year but only the leaf biomass was considered. Accurate modelling of NEP over time is essential for forest carbon inventory projections. Thus, current models rely on growth curves and allometric relationships, which may not be universally applicable. A more robust modelling approach simulates underlying processes affecting forest productivity. Pathak et al. (2018) study on grassland in North-east India showed that harvesting of biomass is one of the major pathways for carbon loss in *Imperata* grasslands and carbon emissions during residue burning and heterotrophic respiration are also major disturbances that impact the annual production. Our study‘s high NEP value can be the result of no harvesting and burning in these plantations. Harvesting of trees or crops along with the burning for cultivation have a detrimental role in NEP.

6.6. Conclusion

This study examined monoculture plantations that were well-managed but not commercially operated during the study period. Monoculture plantation has become a source of livelihood in north-east India as farmers gradually move away from shifting cultivation. This shift had bought the introduction of new crops and plantations such as rubber and oil palm as a prominent new crop.

Litter production peaked in March and April in the selected plantations and was influenced by environmental factors such as increased solar radiation, temperature, and rainfall. Elevation and litter characteristics also played crucial roles in the decomposition rates of the aboveground and belowground litter. Rainfall during the study period enhanced litter breakdown, while reduced precipitation slowed nutrient release, affecting ecosystem nutrient cycling. Variations in leaf morphology contributed to different decomposition rates among the selected plantations, with rubber plantations experiencing faster litter loss due to thinner leaves, while teak plantations had slower decomposition due to thicker leaves limiting water penetration.

Root production peaked in warmer months during the study peri of, with mortality increasing during autumn and winter. Belowground biomass in these plantations was lower than in forests, likely due to soil properties and nutrient availability. Fine root biomass was influenced by soil pH, magnesium concentration, and total carbon content, with warmer temperatures and increased precipitation stimulating root growth. The ingrowth corer method revealed that fine roots had a short lifespan, with growth patterns varying across species. The mortality and decay for both aboveground and belowground also vary with the seasons and rainfall influenced their pattern of variation. The species of each plantation had a key role since their leaves effect the decomposition of litter.

Net primary productivity (NPP) and net ecosystem production (NEP) were influenced by plantation age, with older plantations showing stabilized productivity. Soil respiration peaked during the monsoon season due to increased microbial activity and root respiration. It was also dependent on climatic conditions and the surrounding environment was another detrimental factor in estimating NEP. Carbon sequestration varied across plantations, with higher NEP values in undisturbed sites. The absence of harvesting and burning in these plantations contributed to their higher carbon retention compared to commercial or disturbed sites. However, variations in carbon flux calculations highlight the need for improved modeling techniques to enhance the accuracy of forest carbon assessments.

Overall, this present study showed the importance of environmental conditions, plantation characteristics, and soil properties in shaping biomass production, decomposition rates, and carbon dynamics. Future research should focus on refining carbon budget models and assessing long-term changes in plantation ecosystems to better understand their role in carbon sequestration and climate change mitigation.

CHAPTER VII- GENERAL DISCUSSION

The state of Mizoram is known for its rich natural resources and diverse ecosystems. Plantation-based livelihoods such as oil palm, rubber and agroforestry are emerging as significant contributors to the socio-economic development of the state. Also, the challenges that the farmers faced due to shifting cultivation and its lack of economic viability has caused a shift towards plantation-based livelihood. Studies done by Sati & Vangchhia (2017), Sati (2019), and Sati (2022), had shown that by utilizing the state‘s diverse agro-conditions and water resources, effective management of plantations can elevate rural livelihoods. These plantations have nevertheless increased the income of farmers practising these, besides, these systems have created employment (both direct and indirect) opportunities in rural areas of Mizoram through harvesting, processing and marketing (Sati, 2023).

Sahoo et al. (2023) had studied numerous plantation systems including secondary forests, oil palm, orange and areca nut plantations that were established on degraded shifting cultivation lands and found that plantations such as oil palm, orange and areca nut in Mizoram can be linked to a source of livelihood. Hrahsel & Sahoo (2024) reported that in Mizoram‘s plantation, areca nut plantation in Mizoram has the lowest soil organic carbon stock compared to other plantations while teak plantations demonstrate high soil organic carbon (SOC) stocks indicating good soil fertility and productivity. Lallianthanga et al. (2014) with the use of GIS techniques reported that 29% of the state‘s geographical area is suitable for rubber plantation and successful implementation of rubber plantation may prove beneficial for the farmers and the state government. Thus, plantations in Mizoram have a crucial role in promoting ecological sustainability and supporting the region‘s economic stability.

The lack of adequate market, however, remains a challenge and causes limitation to these farmers. The success of these plantation-based livelihoods in the state heavily depends on the government as effective policy and institutional support can provide support to these farmers. The state government has taken initiatives such as the Oil Palm (Regulation of Production & Processing) Act. 2004, which showed a tremendous increase in oil palm plantation; New Land Use Policy (NLUP) was adapted to reduced shifting cultivation in Mizoram. Although these plantation-based livelihoods provide economic benefits, they could also pose as a threat to the environment. The expansion of land for rubber and oil palm plantations may cause deforestation and loss of biodiversity. There is a critical need for sustainable practices, such as cultivating in degraded land and jhum area so as to reduce the environmental impact (Sati, 2023). If these plantations are managed properly, it can contribute to land restoration and carbon sequestration.

The age of the plantations had a significant role in the amount of biomass and carbon stored by these plantations as it influences the ecosystem structure, function and carbon storage. Older or mature stands experience competition for light and nutrients due to the dense canopy and may affect the carbon understory storage (Haq et al., 2024). The carbon storage varies with the species of plants or trees of the plantation as well as the age of the plantation (Haq et al., 2024). The leaves of the trees also play a factor in the carbon storage of these plantations. The hairy leaf of teak that protects it from insects was found to decompose least rapidly among the selected plantations. Although areca nut and oil palm have high carbon sequestration potential, the present study found that rubber and teak had better sequestration potential. One of the contributing factors could be due to the structure and composition of the stand as well as the disturbances that may have an influence (Gogoi et al., 2017). Mature plantations stock considerable amount of biomass carbon, however they are susceptible to degradation due to clear-felling management system. According to Brahma et al. (2018b), clear-felling of trees can result in a carbon loss ranging from 16 to 178 Mg/ha, even when considering only the loss from aboveground tree biomass. Das et al. (2021) reported that *Areca* plantations have low biomass carbon storage potential and conversion of natural forests into such monoculture plantations can lead to various environmental impacts, particularly in decline of SOC stocks. This reduction may have a negative impact on the soil biological diversity and the ecosystem services it supports.

The analysis of biomass and carbon stock comparisons of the present study with other studies across India‘s north-eastern region was to work towards understanding the plantation carbon dynamics. The biomass and carbon stock values reported for our plantations showed that out plantations have a good potential to be a carbon inventory. Rubber and teak exhibited strong potential to be a source of carbon due to their higher carbon biomass storage, greater soil organic carbon accumulation and their net ecosystem production (NEP).

The quality of leaf litter can be identified as a significant determinant of decomposition rate as well as its contribution on SOC. Zhao et al. (2022) found that broad-leaved forests tend to have faster decomposition rates due to the initial high nutrient concentrations which accelerated decomposition, enhanced nutrient cycling in forest ecosystems, improved soil acidity and organic matter content. The leaf nitrogen content, specific leaf area, leaf dry matter content and leaf tannin content all played a role in litter decomposition. Higher nitrogen content and leaf surface area were associated with faster decomposition while higher leaf dry matter content was linked with slower decomposition (Zhao et al., 2022). When evaluating SOC sequestration and its potential to mitigate climate change on a global scale, it is essential to consider the dynamic nature of soil carbon storage and the interventions that enhance it (Yang et al., 2020). Carbon sequestration of soil generally refers to any increase in SOC content due to changes in land management, with the implication that higher soil carbon storage contributes to climate change mitigation (Lal et al., 2015). Soil carbon sequestration is particularly significant in Mediterranean regions, where climatic conditions and agricultural practices contribute to low SOC content, making it highly susceptible to climate change impacts (Farina et al., 2011).

Decomposition, a complex multi-step process, involves the breakdown of litter through leaching, mechanical and invertebrate fragmentation, and microbial transformation (Gupta & Malik, 1999; Hättenschwiler et al., 2005). Litter decomposition has a crucial role in the global carbon cycle, as it accounts for a major portion of heterotrophic soil respiration and leads to the formation of stable SOC, the largest terrestrial carbon stock (Zhao et al., 2022). Multiple factors can influence litter decomposition, with climate expected to be a dominant factor at global scales. The climate history of the decomposer community is a key determinant of litter decomposition, explaining as much variance in decomposition rates as temperature and moisture (Strickland et al., 2015). The quality of litter may be strongly influenced the respiration of soil, dissolved organic carbon and decomposing fragments (Huang et al., 2011). A long-term study conducted in South China explored how the chemical components of forest debris influence SOC accumulation, employing advanced techniques to partition decomposition products. Research has shown that litter quality strongly influences the partitioning of respiration, dissolved organic carbon (DOC), and decomposing litter fragments (Gupta & Malik, 1999; Hättenschwiler et al., 2005; Strickland et al., 2015). A long-term study in East and South China examined the impact of forest debris' chemical components on SOC accumulation and it was found that the influencing factors varied with soil depth, precipitation and temperature being dominant in the organic horizon, while soil texture played a key role in the mineral horizon (Huang et al., 2011; Liu et al., 2016).

Litter is a fundamental component of nutrient cycling in forest ecosystems. The decomposition of dead organic matter facilitates nutrient activation, influencing all aspects of ecosystem functionality (Giweta, 2020). The relationship between SOC and leaf litter decomposition is essential for understanding ecosystem dynamics across diverse environments. SOC forms through the decomposition of organic matter, which improves soil fertility and structure by directly influencing leaf litter decomposition rates (Giweta, 2020; Y. Liu et al., 2023). With the assistance of microorganisms, this process releases essential nutrients into the ecosystem; thereby reinforcing nutrient cycling. Environmental factors such as temperature and moisture significantly regulate decomposition rates, consequently affecting SOC levels (Giweta, 2020). Across different ecosystems, the inter-relationship between SOC and decomposition rates varies, with climate serving as the dominant influence on these processes. A comprehensive understanding of this relationship is vital for developing effective nutrient management and carbon sequestration strategies, particularly in the face of climate change and its implications for soil health (Y. Liu et al., 2023). Litter fall is an important component of nutrient cycling in forests, this is because they regulate the accumulation of soil organic matter, nutrients input and output, which are important for maintaining ecosystem functions (Giweta, 2020). Several major factors determine litter production and decomposition such as the environmental conditions and biological interactions; however, variability in litter quality and its decomposition rates can have a significant impact on the functioning of forest ecosystems (Huang et al., 2011; Giweta, 2020; Liu et al., 2023). The processes of litter production and decomposition are complex and influenced by a variety of natural and human-induced factors. There are significant gaps regarding the effects of species diversity, forest structure, seasonal changes and climate on litter production and decomposition However, our understanding of these factors remains limited, making it hard to reach general conclusions about their impact (Giweta, 2020).

One of the major pathways of carbon in the selected plantations was through soil and trees, both of which played a crucial role in carbon sequestration and storage. Trees act as carbon sinks by capturing atmospheric carbon dioxide (CO_2) through photosynthesis and storing it in their biomass (trunks, branches, leaves, and roots) (Okorie et al., 2017). In contrast, the soil serves as a long-term carbon reservoir, where organic matter from decomposed plant material contributes to SOC (Lal et al., 2015). Trees in plantations absorb CO_2 and convert it into biomass, effectively reducing atmospheric carbon levels (IPCC, 2019). The rate of carbon sequestration in trees depends on species type, growth rate, and environmental conditions, including soil properties such as pH and bulk density (Li et al., 2023). As leaves and roots decompose, carbon enters the soil, where microbial activity influences its stabilization or release as CO_2 through soil respiration (Schmidt et al., 2011). Soil carbon storage is influenced by factors such as soil texture, moisture, and microbial activity (Gunina et al., 2017). In well-managed plantations, conservation practices like reduced soil disturbance and organic matter retention can enhance SOC levels, making the soil an effective carbon sink. However, disturbances such as deforestation or intensive agriculture can release stored carbon back into the atmosphere, contributing to climate change (Lal et al., 2015). Thus, both trees and soil are integral components of the carbon pathway in the selected plantations, with their ability to sequester carbon influenced by biological and environmental factors. Sustainable management of these components is essential for optimizing carbon storage and mitigating climate change.

Proper management of plantations is crucial for maintain carbon stocks in the ecosystem due to its influence on carbon sequestration and emissions. Effective management of plantation not only enhances the carbon uptake by increasing the biomass accumulation but it also improves the SOC storage, thus contributing to net ecosystem production (NEP). Sustainable plantation management practices such as selective harvesting play a key role in maintaining carbon stocks (Gatkal et al., 2024). In the selected study sites, harvesting was not practiced during the study period, which caused a higher NEP when compared to other studies (Beringer et al., 2007; Grant et al., 2010a; Pathak et al., 2018). Harvesting and burning of plantations significantly affect the carbon dynamics by leading to carbon loss and altering the NEP. They cause stored carbon to be released back to the atmosphere and reduce the plantation‘s role as a carbon sink, thereby potentially turning it into a carbon source. The extent of this impact will depend on the harvesting methods, post-harvest land management and the carbon recovery (Paul et al., 2022). Harvesting in plantations may result in direct loss of aboveground carbon and it may even disturb the SOC stocks (Paul et al., 2022) and it can potentially reduce the litterfall which contributes to the SOC (Y. Liu et al., 2023). Harvesting and burning can disrupt the carbon storage as it lowers the rate of respiration soil and accelerate microbial decomposition (Hu et al., 2021). In cases where burned plantations are not reforested, the land may become degraded, resulting in a persistent loss of carbon storage potential (Houghton, 2013).

The selected plantations exhibited a positive NEP value, indicating their potential to function as carbon sinks. A positive NEP indicates that the ecosystem is acting as a carbon sink, while a negative NEP suggests it is a carbon source. Harvesting and burning plantations contribute significantly to carbon loss by reducing biomass carbon storage and increasing emissions from soil and combustion.

These activities negatively impact NEP, potentially turning plantations from carbon sinks into carbon sources. Thus, proper management may enhance the NEP by maximizing photosynthetic carbon uptake while minimizing carbon release through respiration and decomposition (Law et al., 2001). Minimizing or eliminating burning practices would help in restoring carbon in plantations and prevent soil quality degradation (Houghton, 2013; Hu et al., 2021). Integration of plantation trees with crops may also help in improving the soil fertility, increase biodiversity and ensure sustainable nutrient cycling. Also, conversion of degraded shifting cultivation lands into productive plantations such as rubber, areca nut and oil palm may help in the livelihoods of the farmers while restoring the land (Sahoo et al., 2023).

Plantation-based livelihoods can also provide employment opportunities for farmers in Mizoram. However, without sustainable practices and robust market linkages, these benefits may be undermined. By developing a more robust market linkage as well as support systems for plantation-based products can help overcome some of the challenges. The success of plantation-based livelihoods is heavily reliant on proactive government policies and institutional support. The state government can further support farmers by implementing policies that offer regulatory and financial assistance while promoting sustainable practices. Additionally, initiatives can be introduced to prioritize plantation species with higher carbon sequestration potential, such as rubber and teak, while maintaining genetic diversity. Long-term studies based on the carbon dynamics, litter decomposition rates and ecosystem productivity are also recommended so as to have a better understanding of their inter-relationship and to ensure management practices. Plantations can act as effective carbon sinks and help in land restoration; however, unsustainable expansion of lands for market-profit should be avoided at all cost due to the high risk of biodiversity loss and soil degradation. Implementing these recommendations may help harness the economic potential of plantation-based livelihoods while ensuring the long-term sustainability of Mizoram‘s natural resources and ecosystems.

CHAPTER VIII- SUMMARY AND CONCLUSION

In Mizoram, the main source of livelihood is agriculture and shifting cultivation has been one of the main practices. Shifting cultivation, also known as slash-and-burn agriculture, involves clearing forests, burning debris, and cultivating land for a limited time before allowing it to fallow. Shifting cultivation has been practised in north-eastern states of India for centuries and it has been a traditional agricultural method. The area under shifting cultivation in north-eastern India is significant, with Mizoram having a notable portion of its agricultural land dedicated to this practice. Despite the low production and yield, shifting cultivation remains a vital socio-cultural activity for the farmers. The challenges faced by farmers, including climate variability, soil erosion, and food insecurity. These factors contribute to a high poverty rate in rural areas of Mizoram, necessitating an empirical study to assess the economic implications of shifting cultivation (Sati, 2019).

Mizoram‘s diverse agro-conditions and water resources offer unique opportunities, hence, expansion of plantations for cultivation of rubber and oil palm has a large potential (Lallianthanga et al., 2014; Sati, 2022). Owing to the initiatives taken by the state government in 2004, oil palm cultivation has become an important source of livelihood in the region (Lalawmpuia et al., 2020). Sati (2022) recommended better management of water resources and diversifying crop production or improving small scale forest based industries as viable solutions to persisting issues. To achieve food security as well as the sustainable development of natural resources, strengthening financial and infrastructural base is crucial (Sati & Vangchhia, 2017a, b). The expansion of oil palm plantation for economic benefits may cause harm to the environment, which may pose as a serious challenge in the future of the state (Sati, 2023). Tailoring plantation management practices to local environmental conditions is essential for achieving both economic growth and ecological balance. Local livelihood improvement efforts should promote the restoration of tropical forests while conserving biodiversity as well as enhancing landscape heterogeneity (Brancalion & Chazdon, 2017).

The comparison of biomass and carbon stock in our study with similar studies across India, particularly the north-eastern region, highlights key insights into plantation carbon dynamics. Rubber and teak plantations in the study demonstrated high carbon storage potential, with both biomass and soil significantly contributing to sequestration. However, carbon storage in teak plantations was lower than similar-aged plantations in southern India (Reddy et al., 2014) due to differences in soil conditions, precipitation, and temperature. Oil palm plantations in the present study exhibited lower above-ground biomass accumulation compared to previous studies (Singh et al., 2018), influenced by mortality rates and rainfall patterns. Areca plantations showed significantly lower biomass storage than rubber plantations, aligning with past research (Sujatha et al., 2016; Das et al., 2021). The low carbon storage potential of *Areca* plantations raises environmental concerns, including SOC depletion, reduced soil biodiversity, and increased erosion risks, emphasizing the need for sustainable land-use practices.

The present study found that SOC concentration and stock decrease with soil depth in all the selected plantations. This can negatively impact soil health and productivity, thus, maintaining organic matter in the upper soil layers is crucial for enhancing soil quality and long-term productivity. The selected different plantation types exhibited varying SOC stocks, with teak plantation having the highest and *Areca* nut plantation with the lowest. These findings can guide farmers and land planners in selecting tree species that with the best carbon storage potential and without compromising the soil fertility. It was also revealed there was significant variations in soil properties among plantations, particularly in bulk density, between the oil palm, rubber and teak plantations. Soil nutrients and SOC concentration showed a negative relationship with depth, by decreasing as depth increased, which may impact soil health, productivity, and carbon balance. By increasing litter input through plant residues and improved management practices, the SOC stocks could be maintained. Thus, it provided insights into the role of monoculture plantations in SOC storage, especially as shifting cultivation declines in north-eastern India.

Climatic and anthropogenic factors influenced the litter production, by varying across months and seasons. Furthermore, mortality and decay rates of aboveground and belowground litter varied seasonally, which was influenced by rainfall and species composition, as leaf traits of each plantation may had affected the decomposition. Soil respiration was also climate-dependent, hence, the surrounding environment played a crucial role in determining net ecosystem production (NEP). The absence of harvesting and burning contributed to the higher NEP observed in this present study, when compared to similar research in north-eastern India (Pathak et al., 2018). The interaction between aboveground biomass, soil organic carbon, and litter decomposition was essential for optimizing NEP (Chambers et al., 2001; Zheng et al., 2019; Huang et al., 2024). If plantations are not managed properly, disturbances like harvesting and burning can transform ecosystems from carbon sinks into carbon sources.

The present study highlighted the ongoing transition from shifting cultivation to monoculture plantations in Mizoram by emphasizing both the economic opportunities and environmental challenges associated with this shift. While rubber and teak plantations demonstrated high carbon storage potential, *Areca* plantations had significantly lower biomass storage, raising concerns about soil degradation and biodiversity loss. The findings indicated that SOC concentration and stock decreased with soil depth, thus, there may have long-term effect on their soil health and productivity. Variations in soil properties, particularly bulk density and nutrient distribution, underscored the need for tailored management practices. Climatic and anthropogenic factors influenced litter production, decomposition, and soil respiration, all of which played a crucial role in determining net ecosystem production (NEP). It can be suggested that sustainable plantation management practices, such as maintaining organic matter and minimizing disturbances are essential to optimizing carbon sequestration while balancing economic and ecological needs.

PHOTOS PLATES

Photo plate 1: Tree GBH measurement taken using measuring tape.

Photo plate 2: Litter collection from selected plantations

Photo plate 3: Soil collections at different sites during the study period.

Photo plate 4: Litter traps and litter production on selected plantations.

Photo plate 5: Litter bags laid on selected plantations.

Photo plate 6: Fine root biomass estimation

Photo plate 7: Sorting of live and dead roots.

Photo plate 8: Fine root decomposition bags.

Photo plate 9: Soil respiration measured using Q-Box SR1LP.

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PUBLICATIONS

1. **Hrahsel, L.**, Sahoo, U.K (2024). Variation of Soil Organic Carbon in Different Plantations in Mizoram. *International Journal of Ecology and Environmental Sciences* (50), p.393—404. https://doi.org/10.55863/ijees.2024.0036

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3. **Hrahsel, L.,** Sahoo, S. S., Singh, S. L. & Sahoo, U. K., (January—March 2019). Assessment of Plant Diversity and Carbon Stock of a Sub-Tropical Forest Stand of Mizoram, India. *Environment and Ecology* , 37(1A), p. 229—237.

SEMINARS ATTENDED

1. Poster presentation on **—Litter fall Decomposition and Soil organic carbon stock in oil palm plantation in Aizawl, Mizoram, India‖** International Conference on —Biodiversity, Biogeochemistry and Ecosystem Sustainability in Changing Environment‖ organised by Indian Ecological Society and Department of Forestry, Mizoram University, held on 14th – 16th June 2023
2. Oral presentation on **—Soil Organic Carbon (SOC) sequestration under *Tectona grandis* (Teak) plantation in Aizawl, Mizoram, India‖** on National Seminar on —Utilization and Conservation of Plant Resources for Sustainable Development‖ organised by Biodiversity Research Centre (BRC), Department of Environmental Science, Mizoram University, held on 1st – 2nd June 2023
3. Poster presentation on **—Soil Organic Carbon Sequestration under *Hevea brasiliensis* (Rubber) plantation in Mizoram, India‖** in National Conference on —Natural Farming Systems and Biodiversity Conservation under Changing Climate Scenario‖ organised by National Academy of Agricultural Sciences (NAAS), International Union of Organic Agriculture (IUOA) and College of Agriculture (CAU), held on 5th-7th December 2022.

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DEPARTMENT	: Forestry
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APPROVAL OF RESEARCH PROPOSAL	
1. DRC	: 08.05.2020
2. BOARD OF SCHOOL	: 11.05.2020
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ABSTRACT

ASSESSMENT OF NET ECOSYSTEM PRODUCTION AND CARBON DYNAMICS IN SELECTED TREE PLANTATIONS OF MIZORAM

AN ABSTRACT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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DEPARTMENT OF FORESTRY
SCHOOL OF EARTH SCIENCE AND NATURAL RESOURCE MANAGEMENT

MARCH, 2025

ASSESSMENT OF NET ECOSYSTEM PRODUCTION AND CARBON DYNAMICS IN SELECTED TREE PLANTATIONS OF MIZORAM

BY

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DEPARTMENT OF FORESTRY

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Submitted

In partial fulfillment of the requirement of the Degree of Doctor of Philosophy in Forestry of Mizoram University, Aizawl.

INTRODUCTION

The state of Mizoram is heavily dependent on agriculture for its economy and shifting cultivation has been a traditional agricultural practice in Mizoram. The is unsustainable due to increase in deforestation, soil erosion and declining soil health. However, there is a gradual change from shifting cultivation to a more sustainable form of agriculture amongst the farmers. Plantation crops such as rubber, oil palm, areca nut etc. are on the rise and this transition is also supported by the state government through initiatives that aims at improving sustainability, stable livelihoods to the farmers and reduce environmental degradation. This shift to plantations is expected to provide not only long-term economic benefits but reduce the adverse effects on the environment.

The present study was conducted on four monoculture plantations – rubber, oil palm, areca nut and teak, located Sakawrtuichhun and PTC Lungverh, Aizawl, Mizoram, 15 years at the time of data collection, well-maintained over a period of three years (December 2020 to December 2023). Thus, they serve as representative models for assessing their potential in carbon inventory management.

The present study was conducted with the following objectives:

1. Estimation of the biomass and carbon stock potential of these plantation using allometric models,
2. Assessment of soil physico-chemical properties with an emphasis on C inventory of soils (active and passive C pools) of these plantations and
3. To assess the net ecosystem productivity (NEP) by evaluating the C losses by heterotrophs (through studies of litter production and decay rates, mortality of above and belowground and soil respiration etc) of these four plantations.

The study was conducted using standard methods. The salient features of the results are as follows:

- Among the plantations, rubber had the highest total biomass (101.36 ± 4.57 Mg ha^{-1}) and aboveground biomass carbon (50.68 ± 2.235 Mg C ha^{-1}). Tree biomass and biomass carbon among the plantations followed this order: Rubber > Teak > Oil Palm > Areca Nut.
- The GBH of each plantation have a positive relationship with their height, thus the trees' GBH from the selected sites will increase with their height.
- Areca nut plantation had the highest litter biomass (1.116 ± 0.30 Mg ha^{-1}) while deadwood biomass was in the highest in oil palm plantation (2.351 ± 0.1 Mg ha^{-1})
- Rubber and teak plantations showed high carbon sequestration potential amongst the plantations.
- Areca plantations have low potential for biomass carbon storage and conversion of natural forests into such monoculture plantation can thus have a varied environmental impacts and disservice to the ecosystem, in particular, reduction of SOC stocks.
- The pH of all plantations was mildly acidic, and they follow a similar pattern since they all increased with the increase in depth of the soil.
- Areca nut plantation was found to have the lowest pH amongst the selected plantations with pH at 4.78 in 0-20 cm soil depth and 4.94 in 20-40 cm soil depth. The highest pH was seen in rubber plantation with 0-20 cm soil depth having pH value of 5.59 and 20-40 cm depth with pH 5.75.
- The moisture content and bulk density was found increasing with the increase in soil depth. These also significantly ($p < 0.005$) varied between the plantations.
- The moisture content was seen in the following order: Teak < Areca Nut < Oil Palm < Rubber, whereas the bulk density was in the order: Oil Palm < Areca nut< Teak < Rubber.

- SOC concentrations varied between the plantation and ranged from 1.17 – 1.92% while SOC stock was found in the range: 26.05 Mg C ha^{-1} (oil palm plantation) to 49.09 Mg C ha^{-1}(teak plantation). Both SOC concentration and SOC stock decreased with increase in soil depth and this was true for all the plantations.
- The soil carbon (%), available nitrogen, potassium, magnesium and calcium decreased with increase in the soil depth in all the plantations
- A significant variation was found in the total carbon content (%) between rubber and areca nut plantations.
- All soil nutrients showed a significant decrease with increase in soil depth and this was true for all plantations..
- There was a distinct variation between active and passive C pools and the active carbon pool was found to be always higher than the passive carbon pool in all plantations.
- Among the plantations, areca nut had the highest very labile carbon stock while rubber plantation had the lowest very labile carbon stock.
- Rubber plantation too had the highest recalcitrant (less labile and non-labile) carbon pool while oil palm plantation had the lowest less labile and non-labile carbon.
- Litter production varied yearly and between the plantations. Peak litter production in all the plantations was observed during March to April 2023.
- The litter mass loss (%) was almost constant in rubber and oil palm plantations.
- Areca nut and teak plantation observed increased mass loss during the monsoon seasons.
- Fine root mass loss showed a positive relationship with the rainfall during the study period.
- Rubber and Areca nut had their fine root biomass production peaked in January to March 2023 while oil palm and teak plantations' fine root biomass production peaked during April and June 2023.

- Aboveground mortality for rubber and oil palm was highest during the month of March and April while areca nut and teak had high aboveground mortality during the winter seasons (January and November).
- Belowground mortality for all plantations was the highest during October to December 2022.
- The Net Primary Productivity (NPP) was the highest in Rubber plantation and lowest in Areca nut plantation.
- The soil respiration highest in rainy season for all plantations and teak plantation had the highest soil respiration
- The Net Ecosystem Production (NEP) was observed to be the highest in Rubber plantation (155.4±7 Mg $Cha^{-1}yr^{-1}$) and lowest in Areca nut plantation (40.9±3 Mg $ha^{-1}yr^{-1}$).
- The plantations all showed a positive NEP value, thus indicating that they may serve as potential carbon sink.

The findings showed that all the plantations have the potential to offer a varying degree of carbon capture and sequestration. This could emerge an effective strategy for carbon management particularly in understocked and degraded forests, and presently the state government has focused on bringing the understocked and degraded forest patches under the cash-remunerative tree plantations. The study further suggests significance of rubber as an appropriate tree plantation to harmonize better ecosystem service to the farmers. The living and litter carbon in the plantations also contributed to cumulative carbon balance in these systems. Under the current climate change, the forest plantations are crucial to climate change mitigation, and therefore, the interconnection of carbon management with ecosystem functionality can promote sustainable land management Both rubber and teak plantations exhibited high carbon sequestration potential, making them valuable for climate change mitigation while areca nut and oil palm plantations showed lower biomass carbon storage and potential risks to soil health and biodiversity, raising concerns about long-term sustainability. Furthermore, long-term studies on carbon dynamics, litter decomposition, and ecosystem productivity are important for informed management decisions.