Forests and Carbon Sequestration

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Edited by

Mohd Nazip Suratman, Seca Gandaseca and Zulkiflee Abd Latif

Cambridge Scholars Publishing

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This book first published 2025

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-1-0364-1742-0
ISBN (Ebook): 978-1-0364-1743-7

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PART A:

INTRODUCTION TO FORESTS AND CARBON SEQUESTRATION

CARBON SEQUESTRATION POTENTIAL IN NATURAL AND PLANTATION FORESTS

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Introduction

The forests of the world hold large stores of carbon. Carbon is stored in various components of forests. Biomass is an organic make up of both living and dead materials, e.g., trees, crops, grasses, tree litter, roots, etc. The biomass of trees or vegetation is often subdivided into above-ground biomass (AGB) and below-ground biomass (BGB) components with further subdivisions of each. AGB is all biomass living above the soil including stem, stump, branches, bark, seeds, and foliage whereas BGB is the entire biomass of live roots. Total tree biomass (TTB) combines both AGB and BGB and represents the entire mass of the tree. Biomass contains stored chemical energy from the sun. Plants produce biomass through photosynthesis. During this process, plants convert radiant energy from the sun into chemical energy in the form of glucose. Through photosynthesis, plants absorb carbon dioxide (CO_2) from the atmosphere and store the carbon. The removal of CO_2 from the atmosphere by forests helps mitigate the impacts of climate change.

An accurate estimation of biomass, especially in the forests, is essential for many applications. This ranges from commercial exploitation of timber and national developmental planning to scientific uses such as studies of ecosystem productivity, energy and nutrient flows, and for evaluating the impact of changes in tropical forests on the global carbon cycle (Gillespie et al., 1992; Basuki et al., 2009). From the environmental viewpoint, it is an essential aspect of studies of carbon stocks and the effects of deforestation and carbon sequestration on the global carbon balance as well as providing valuable information for many global issues (Brown, 1997; Kueh and Lim, 1999; Keller et al., 2001; Mani and Parthasarathy, 2007). For commercial purposes, the estimation of biomass is useful to assess the timber resource available for logging and to assess the quantity of sawn timber by making volume estimation (Brown, 1997).

Biomass can be estimated through destructive and non-destructive methods by which the pros and cons lie in both ways. The destructive method is a direct measurement of trees by tree harvesting. This method requires the felling of a tree, and weighing the tree section in order to obtain the actual weight or density of biomass. Estimation of biomass through destructive methods is more accurate than non-destructive. However, destructive methods are time-consuming, labour intensive and costly (Basuki et al., 2009). Non-destructive method on the other hand does not require the felling of a tree thus less costly to be performed and not destructive. The method requires the collection of forest inventory data usually involving tree diameter at breast height (DBH) and tree height. These data are used to estimate the tree biomass or tree volume. Published allometric functions can be applied to obtain biomass estimation. Published regression equations can also be applied provided the tree samples are from the same habitat or the same species. However, this method will provide less accurate biomass. For example, Cairns et al. (2003) reported a comparison between actual tree biomass obtained from the felling of 195 trees in Mexico's Yucatan Peninsula with tree biomass calculated with the published biomass model developed by Brown (1997). They found that the published model underestimated the biomass of these trees by 31%.

Carbon stocks refer to the amount of carbon stored in the forests at a given point in time. Carbon stocks in AGB are typically derived by assuming that 50% of the biomass is made of carbon using allometric equations. Carbon stock assessments in the natural and plantation forests are vital to determine the major role of each component contributing to overall carbon stocks. Hence, the forest ecosystem services are important to climate change mitigation, acting as carbon sinks.

The natural forest consists of primary and secondary forests. A primary forest is a forest that has never been logged and has developed following natural disturbances and under natural processes, regardless of its age. It is referred to as direct human disturbance as the intentional clearing of forest by any means (including fires) to manage or alter them for human use, meanwhile, a secondary forest is a forest that has been logged and has recovered naturally or artificially. Not all secondary forests provide the same value to sustaining biological diversity, or goods and services, as primary forests in the same location. A plantation forest may be afforested land or a secondary forest established by planting or direct seeding. A gradient exists among plantation forests from even-aged, single-species monocultures of exotic species with a fibre production objective to mixed species, native to the site with both fibre and biodiversity objectives. This gradient will probably also reflect the capability of the plantation forest to maintain normal local biological diversity (Convention on Biological Diversity 2006). This chapter provides an overview of carbon sequestration mechanisms in the forests and examines the carbon sequestration potential of natural and plantation forests by emphasizing their ability to accumulate biomass and contribute to carbon storage.

Understanding Carbon Sequestration

Carbon sequestration refers to the process of capturing CO_2 from the atmosphere and storing it in long-term reservoirs, in this case, forests, to mitigate global warming and climate change (Suratman, 2008). Once captured, the CO_2 gas (or the carbon portion of the CO_2) is put into long-term storage. Figure 1 illustrates the general carbon sequestration process whereby CO_2 is removed from the atmosphere by a tree and stored in biomass and soils. Trees absorb CO_2 from the atmosphere during photosynthesis, using sunlight, water, and nutrients to convert CO_2 into organic carbon compounds such as sugars and cellulose. This process releases oxygen (O_2) as a byproduct. Carbon stored in trees' biomass (trunks, branches, leaves) represents a significant portion of carbon sequestered in forests.

The growth of trees leads to the accumulation of biomass, thereby sequestering more carbon over time. As carbon is stored in plant cells as a product of photosynthesis, the net effect on the growing plant is the increase in tree height and diameter. The height growth in the tree is mostly made from the reserved carbohydrates in the tree rather than the products from recent photosynthesis. In contrast to the tree height, the carbohydrates from recent photosynthesis are utilised for diameter growth (Kozlowski, 1962).

Carbon is also stored in forest soils in the form of organic matter. The decomposition of plant litter and root biomass contributes to soil carbon storage. In summary, carbon in forests undergoes continuous cycling between the atmosphere, vegetation, litter, soil, and microbial communities (Figure 1). Understanding the rates and processes involved in carbon cycling is essential for accurately assessing carbon sequestration potential from the vegetation.

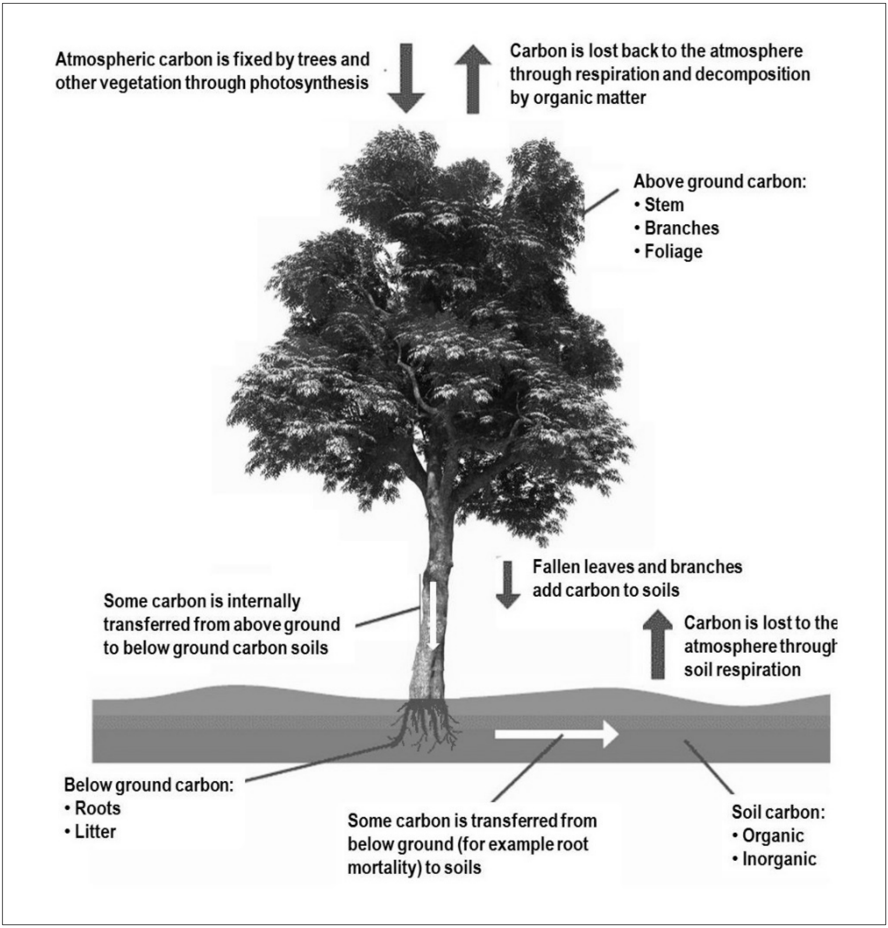

Figure 1: General carbon sequestration process in the forests. [modified from Schahczenski and Hill (2009)].

Carbon Sequestration in Natural Forests

Carbon sequestration in natural forests is a critical process that helps mitigate climate change by removing CO_2 from the atmosphere and storing it in trees, vegetation, and soils. The unit of carbon sequestration typically used is metric tons or megagram (Mg) of carbon per hectare per year (t C ha^{-1} yr^{-1}). This unit represents the amount of carbon that is removed from the atmosphere and stored in a particular area (hectare) of land over the course of one year. Whereas the unit for carbon stocks is typically expressed as metric tons or megagram (Mg) of carbon (C) per hectare (t C ha^{-1}). This unit represents the amount of carbon stored within a given area of land (hectare). Carbon sequestration and carbon stocks are interconnected and influence each other dynamically. Changes in carbon sequestration rates can lead to changes in carbon stocks, and vice versa. For instance, an increase in forest growth (carbon sequestration) results in more carbon being stored in biomass, leading to an increase in carbon stocks. Conversely, deforestation or forest degradation reduces carbon sequestration, causing a decline in carbon stocks.

Carbon stocks in forests vary depending on factors such as tree species, age, climate, soil conditions, and disturbance history. Tropical rainforests are the most carbon-rich ecosystems on Earth as compared to other forest types due to their high biomass density (Table 1). They typically have multiple layers of vegetation, including tall trees, understory shrubs, and epiphytes, contributing to high AGB. Additionally, tropical rainforest soils can store significant amounts of carbon, although the depth and carbon content may vary depending on factors like soil type and drainage. Soils in tropical forests have only modest levels due to the rapid composition of dead biomass in humid and warm conditions; therefore, the leaching out process occurs rapidly.

Table 1. Average carbon stocks for various biomes and soil carbon pools down to a depth of 1 m (Intergovernmental Panel on Climate Change, 2009).

Biome	**Carbon stocks (t C ha^{-1})**		
	Plants	**Soil**	**Total**
Tropical forests	212	216	428
Temperate forests	59	100	159
Boreal forests	88	471	559
Tropical savannas	66	264	330
Temperate grasslands	9	295	304
Deserts and semideserts	8	191	199
Tundra	6	212	127
Wetlands	15	225	240
Croplands	3	128	131

Within tropical forests, there are significant differences in carbon sequestration potential due to various factors such as environmental conditions, species composition, structure, and ecological characteristics, leading to variations in carbon storage. Table 2 shows results from the analysis of AGB, BGB and TTB (t ha^{-1}) of three forest types i.e., lowland dipterocarp, riparian and hill dipterocarp forests, in Pahang National Park, Malaysia (Zani et al., 2018). The result indicates that there are significant differences in these biomass values across the forest types at a significance level of $p \leq 0.05$. This finding suggests that the different forest types have varying levels of biomass, both above and below ground, as well as in total.

It was observed that hill dipterocarp forests recorded significantly higher means of AGB, BGB and TTB than lowland dipterocarp and riparian forests with the values of 500.0 t C ha^{-1}, 85.3 t C ha^{-1} and 585.3 t C ha^{-1}, respectively ($p \leq 0.05$) (Table 2). This is due to the reason that the hill dipterocarp forests comprise the highest number of trees and basal area compared to lowland dipterocarp and riparian forests. The family of Dipterocarpaceae contributed 10% of the total individuals in hill dipterocarp forests. The dominance of dipterocarp trees, particularly *Shorea curtisii* (Meranti seraya), with heights ranging from 30 m to 45 m, indicates their importance in forming the emergent layer of the forest. While Dipterocarpaceae was not the highest in terms of tree density in the forest, they contributed the most in basal area with a value of 13.91 m^2 ha^{-1} (Table not shown). Given that basal area is correlated with stem biomass, the higher basal area in hill dipterocarp forests implies a greater amount of biomass. This, in turn, contributes to higher values of AGB, BGB and TTB in hill dipterocarp forests.

Table 2: Analysis of AGB, BGB and TTB between lowland dipterocarp, riparian and hill dipterocarp forests of Taman Negara Pahang (Zani et al., 2018).

Biomass (t C ha^{-1})	**Lowland dipterocarps**	**Riparian**	**Hill dipterocarps**
Above ground biomass (AGB)	356.8^b	276.1^b	500.0^a
Below ground biomass (BGB)	61.2^b	47.2^b	85.3^a
Total tree biomass (TTB)	418.0^b	323.3^b	585.3^a

Notes: Means with the same letters indicate no significant difference ($p \leq 0.05$).

Despite the high density of *Elateriospermum tapos* (Perah) in lowland dipterocarp forests (i.e., 90 trees ha^{-1}), the basal area is relatively low at 3.10 m^2 ha^{-1}. This implies that although there are many trees, they may be smaller in size or have smaller stems compared to those in lowland and hill dipterocarp forests. Riparian forests, which grow along riverbanks and watercourses, often have unique ecological dynamics influenced by hydrological fluctuations. These factors can shape the composition and structure of riparian vegetation. The forest tends to be characterized by smaller trees, with diameters ranging from 10 cm to 30 cm, occasionally exceeding 40 cm. This suggests that the trees in riparian forests may not reach the same size as those in lowland or hill dipterocarp forests due to factors such as competition for resources or flooding disturbances.

Kueh and Lim (1999) recorded lower AGB in their study in the logged-over Air Hitam Forest Reserve in Selangor, Malaysia where the pioneer species such as *Macaranga* spp. (Mahang), *Sapium* spp. (Kasai) and *Endospermum diadenum* (Sesenduk) were present in high density with the DBH range of 20.6 cm – 25.8 cm. The AGB for Air Hitam Forest Reserve was in the range of 83.69 t C ha^{-1} to 232.39 t C ha^{-1}. The lower value compared to Zani et al. (2018) study might suggest that the forest stand is in an early stage of succession and in the process of recovery after disturbances. Meanwhile, in a study in the Brazilian Amazon Forest, Cummings et al. (2002) found differences in different forest types within the region whereby the mean of AGB for open, dense and acetone forests were 313 t C ha^{-1}, 377 t C ha^{-1} and 350 t C ha^{-1}, respectively.

Carbon Sequestration in Plantation Forests

Plantation forests serve as a nature-based solution for sequestering atmospheric carbon, thereby helping to mitigate anthropogenic climate change. According to the Global Forest Resources Assessment 2020 Main Report, the total area of planted forests worldwide is estimated at 294 million hectares, which accounts for 7 percent of the global forest area. Establishing plantation forests significantly enhances carbon storage in terrestrial ecosystems (Moomaw et al., 2019). However, the effect of different vegetation types on the ecosystem's carbon sequestration capacity is not completely understood (Huang et al., 2023). In addition, there is a lack of scientific knowledge regarding the carbon sequestration capabilities of various plantation tree species, which complicates the selection of species for optimal carbon sequestration. Therefore, understanding the carbon sink potential of planted forests is crucial for achieving carbon neutrality through nature-based solutions.

It is clear that vegetation types have a significant impact on carbon sequestration, making it crucial to accurately assess their effect on ecosystem carbon storage. This assessment is vital for choosing effective forest management strategies. While it is well established that vegetation type greatly influences aboveground biomass carbon storage in forests (Yin et al., 2015; Mensah et al. 2016), its impact on the carbon stock of tree roots, understory vegetation, litter, and soil is less well studied. These components are essential for carbon storage and cycling in forest ecosystems (Kang et al., 2006; Justine et al., 2017). For instance, in subtropical pine plantations, soil carbon stocks accounted for up to 76.6%, vegetation for 22.9%, and forest understory and deadfall layers for 0.6% of ecosystem carbon storage. Furthermore, a carbon concentration factor of 0.5 is often used to estimate plant carbon stocks (Thomas and Martin, 2012). However, C concentrations vary among different tree species and different organs of the same tree species, deviating from 0.5, which leads to uncertainty in estimating vegetation carbon stocks using this factor (Watzlawick et al., 2014). Therefore, more field measurements are necessary to accurately determine the carbon sequestration capacity of forest ecosystems as carbon sinks and to compare differences between plantations with various vegetation types.

Intensively managed plantation forests worldwide significantly contribute to climate change mitigation, necessitating an evaluation of their long-term carbon dynamics. A study by Jiaojiao et al., (2022) in Lishui, southern China, examined the carbon cycling patterns of three typical plantation species *Cunninghamia lanceolata* (Chinese fir), *Cyclobalanopsis glauca* (ring-cupped oak) and *Pinus massoniana* (Masson pine). They used an integrated biosphere simulator (IBIS) with localized parameters and a state-and-transition simulation model (STSM) to evaluate the effects of active forest management (AFM) on carbon storage, incorporating forest disturbance history and carbon cycle regimes. The study found that oak plantations had lower carbon stock in their early years (<50 years) but higher carbon stock in later years (>50 years) compared to Chinese fir and pine plantations. The carbon densities of pine and Chinese fir plantations peaked at 70 and 64 years, respectively, while oak plantation carbon density continued to increase beyond 100 years. From 1989 to 2019, the total carbon pools of the three plantation ecosystems increased annually by 0.16–0.22 Tg C, primarily in the AGB carbon pool. AFM improved carbon storage recovery in pine and Chinese fir plantations after 1996 and 2009, respectively, but not in oak plantations.

Recent research has highlighted that specific forest management strategies can enhance carbon sequestration capacity and soil organic carbon (SOC) storage (Ameray et al., 2021). Traditionally, understory plants are removed from planted forests to reduce competition with cultivated trees for nutrients and water (Zhang et al., 2022). Lime application is a common forestry practice in humid tropics and subtropics to prevent or alleviate soil acidification (Xue et al., 2010). However, both understory removal and lime application have been found to inhibit total soil respiration. Interestingly, the presence of understory plants can counteract the increase in heterotrophic respiration induced by lime application. Comparative analysis showed that the ecosystem carbon density of *Schima superba* (Chinese gugertree) plantations exceeded that of *P. elliottii* (Slash pine) and *P. massoniana* plantations, primarily due to differences in plant biomass carbon density rather than SOC storage. This suggests that broad-leaved planted forests may have higher ecosystem carbon storage in subtropical regions. Xanthopoulos et al. (2023) examined carbon stocks in a *Robinia pseudoacacia* L. (Black locust) planted forest at a lignite centre in Greece and its relationship with stand age. They found that litterfall, along with fine roots, fueled SOC, with SOC accrual declining with age, indicative of SOC accumulation derived from black locust. ABG and BGB carbon showed a linear increase with age. These findings enhance our understanding of carbon accumulation in the restoration of planted forests in degraded post-mining areas.

The collective findings from these studies emphasize the crucial role of tree species in carbon accumulation within plant biomass. Different tree species have varying capacities to sequester carbon, significantly impacting the overall carbon storage of a forest. They also demonstrate that understory plants, which grow beneath the forest canopy, play a significant role in mediating soil organic carbon SOC dynamics. These plants contribute to the input of organic matter into the soil and influence the microbial activity that drives SOC decomposition and stabilization. Notably, the mechanisms regulating SOC vary between topsoil and subsoil, with topsoil generally experiencing more rapid carbon turnover and subsoil having more stable carbon reserves.

Continued research is essential to better understand the carbon sequestration mechanisms associated with tree functional traits, such as leaf area, root depth, and wood density, which affect how trees capture and store carbon. Additionally, investigating the effects of forest plantation management strategies on ecosystem carbon density is crucial. Management practices, such as thinning, species selection, and fertilization, can alter the carbon balance of plantations. The impact of stand age on the carbon sink capacity of mature forests also warrants further study, as older forests may have different carbon dynamics compared to younger forests. This knowledge is vital for improving the management of planted forests. Effective management practices that maintain and enhance the carbon sink function of forests could play a significant role in mitigating rising atmospheric CO_2 levels. By optimizing tree species selection, understory management, and plantation practices, we can maximize the carbon sequestration potential of forests, contributing to global efforts to combat climate change.

Carbon Stock Estimation Using Remote Sensing

Remote sensing data from LiDAR (Light Detection and Ranging) and WorldView-3 imagery were used as primary data sources to develop carbon stock predictive models in the lowland dipterocarp forests in Air Hitam, Selangor, Malaysia (Mohd Zaki et al., 2016). In the initial phase of the study, image segmentation was conducted using object-based image analysis (OBIA), as depicted in Figure 2. This process involved identifying groups of pixels within the digital image that could be associated with specific objects, in this case, tree crowns. These identified groups of pixels are referred to as image objects. Image objects are considered as fundamental entities that consist of similar digital values and possess intrinsic sizes, shapes, and geographic relationships with the real-world scene they represent.

Following the segmentation process, the accuracy of the segmented polygons was assessed by comparing them to reference polygons derived from manual delineation. This comparison involved a 1:1 matching between the reference polygons and the segmented polygons. The accuracy assessment aimed to evaluate how well the segmented polygons aligned with the original image. The metric used to quantify the goodness of fit between the segmented polygons and the original image is D, where lower values of D indicate better fits. D is a measure of dissimilarity or deviation between the segmented polygons and the reference polygons. A lower D value indicates a closer match between the segmented polygons and the reference polygons, reflecting higher accuracy in the segmentation process.

Table 3 summarizes the results from the segmentation process, indicating an average accuracy of 79.5%. Out of the 288 manually delineated tree crowns, 266 were successfully matched, resulting in a match rate of 78%. Additionally, the analysis produced values for over-segmentation and under-segmentation, which were 0.19 and 0.11, respectively, with a D value of 0.19. These metrics provide insights into the performance of the segmentation process in accurately delineating individual tree crowns from the imagery. The match rate indicates the percentage of manually delineated tree crowns that were correctly identified by the segmentation algorithm. Meanwhile, over-segmentation refers to the splitting of single tree crowns into multiple segments, while under-segmentation indicates the merging of multiple tree crowns into a single segment.

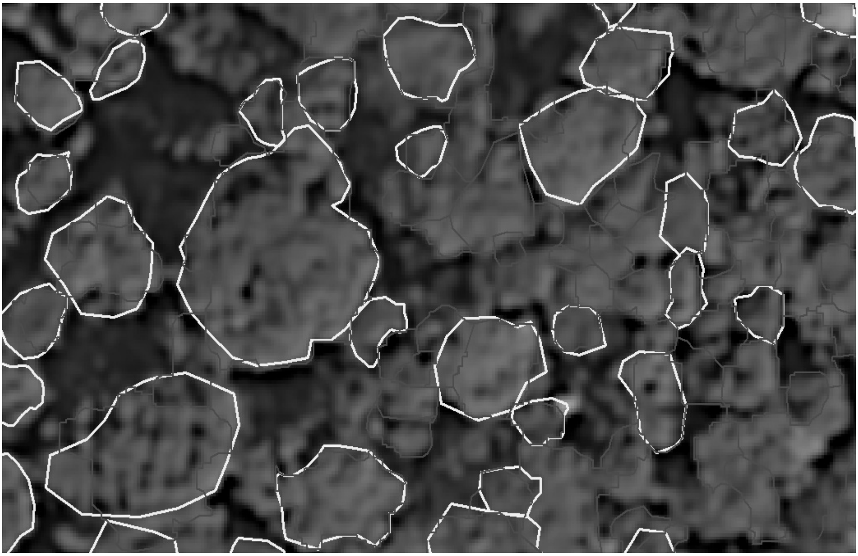

Figure 2: OBIA delineation of tree crowns of a subset area. Red lines are segmented polygons and yellow depicts the reference polygons (Mohd Zaki et al., 2016).

Table 3: An accuracy table from OBIA segmentation (Mohd Zaki et al., 2016).

Table head	Segmentation accuracy				
	Total reference polygon	Total 1:1 match	OS	US	D
1:1	288	266			
Goodness of fit			0.19	0.11	0.19
Total accuracy		78%			81%

Notes: OS = Over segmentation, US = Under segmentation and D = Goodness of fit

A correlation matrix generated indicated the relationships found to exist between carbon stocks versus tree variables (Table 4). Carbon stocks demonstrated a strong and significant relationship with tree heights both measured from the field (r=0.82) and estimated from LiDAR (r=0.71) (all p values ≤ 0.001). DBH and crown projection area were also found to be significantly correlated with carbon stocks with correlation coefficients of 0.91 and 0.67, respectively.

Table 4: Correlation matrix of carbon stocks, DBH, tree height and crown projection area (n=183) (Mohd Zaki et al., 2016).

Variable	Carbon stocks	DBH	H_LiDAR	CPA	H_field
Carbon stocks	1.00				
DBH	0.91	1.00			
H-LiDAR	0.71	0.76	1.00		
CPA	0.67	0.72	0.55	1.00	
H_field	0.82	0.76	0.99	0.56	1.00

Notes: all correlations are significant at the 0.001 significance level.
H_LiDAR = tree height estimated from LiDAR.
H_field = tree height measured from the field.
CPA = crown projection area.

A study was conducted by Suratman et al., (2022) focusing on estimating and mapping spatial distribution of total carbon stocks in Ulu Sebuyau and Gunung Lesong National Parks, located in Sarawak, Malaysia. They employed remote sensing techniques by utilizing satellite imagery from the Sentinel-2A sensor as the primary data source for the study. The study has produced findings on the distribution of total carbon stocks throughout the study area. Varying levels of total carbon stocks across the landscapes were visualized through graduated colors (Figure 3). This visualization provides insights into the variation of carbon storage within the national parks, highlighting areas with higher and lower carbon stocks. Such a map is crucial for understanding the carbon dynamics of the ecosystem and can inform conservation and management efforts aimed at preserving and enhancing carbon sequestration in these valuable natural areas. In addition, the findings of this study also suggest that remote sensing techniques have proven useful in providing valuable spectral and spatial data across large areas. This has enabled the identification of various land cover types and vegetation characteristics, essential for estimating total carbon stocks in Ulu Sebuyau and Gunung Lesong National Parks.

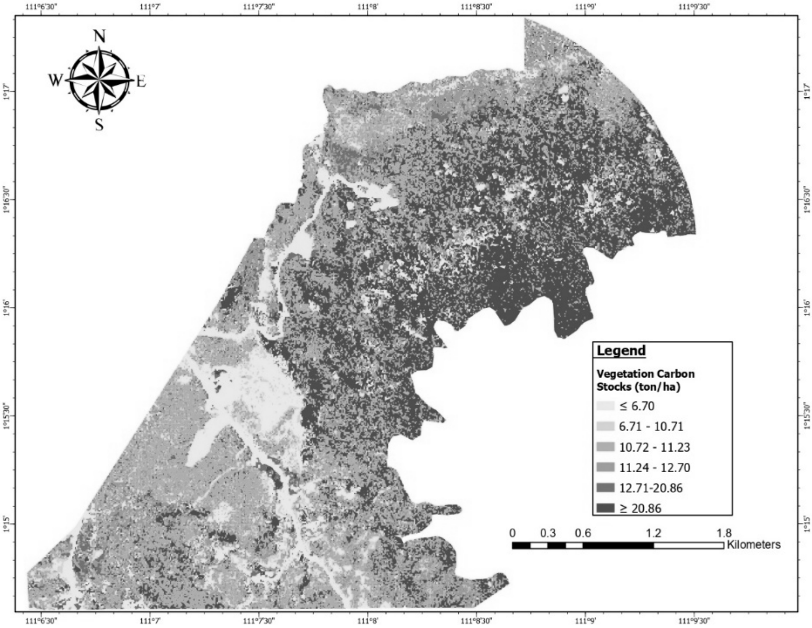

Figure 3: A spatial map presents an overview of total carbon stocks in the study area in Ulu Sebuyau and Gunung Lesong National Parks, Sarawak, Malaysia (Suratman et al., 2022).

The spatial distribution of total carbon stocks in the study area reveals six distinct classes, with values ranging from ≤ 6.70 t C ha^{-1} to ≥ 20.86 t C ha^{-1}. The mixed dipterocarp forests exhibit the highest total carbon stocks, attributed to the presence of dominant tree species such as *Shorea macrophylla* (Engkabang), *Pentaspadon motleyi* (Plajau), and *Shorea maxwelliana* (Selangan batu), which reach maximum DBH. Other land use classes in the study area include old rubber plantations, peat swamp forests, heath forests, resam and grasslands, and clear areas. It has been observed that previous selective logging and land cover changes may have contributed to a diminished total carbon stock in study areas. This underscores the importance of considering land management practices and their impacts on carbon sequestration when evaluating carbon stocks in different ecosystems.

Biomass and Carbon Stock Estimations in Mangrove Forests

Mangroves are considered as dominant ecosystem that can be recognized by their habitat that grow in intertidal zone along tropical and subtropical coastlines, river estuaries or tidal marshes inundated by sea at high tide (Suratman, 2008). The unique characteristics and adaptations of these halophytic plants make mangroves a suitable ecosystem that can tolerate harsh coastal environment (Kathiresan and Bingham, 2001). The total extent of mangrove area in tropical and sub-tropical is estimated around 15.2 million ha, with the Southeast Asia holds about 33% of world total mangrove area (Spalding et al., 2010). Mangroves provide numerous benefits such as ecological values to the environment (Alongi, 2002; Barbier, 2007) and socio-economic support to human (Hossain, 2009).

While mangroves offer numerous benefits, this ecosystem has been degraded at an alarming rate. The climate change scenario coupled with anthropogenic activities such as deforestations (Spalding et al., 2010) has made mangroves becoming plant in peril and contributing to the source of carbon. The increasing carbon from anthropogenic activities in the atmosphere accelerates the global warming phenomenon. One of the critically important services that are being offered by mangroves is the ability to store carbon. According to Kauffman et al. (2011) and Kaufman and Cole (2010), AGB for riverine and fringe mangroves were estimated to be about 500 t C ha^{-1} and for dwarf mangrove of about 8 t C ha^{-1}. The strategic location of mangroves in the coastal area, where the rapid exchange of sediment, organic materials and gases take place between the land and sea provide opportunity for carbon sequestration potential in mangroves. Furthermore, the dead materials from the mangrove trees that fall into the ecosystem does not completely compose but sink as decomposed organic matter and this is important for carbon sink (Suratman, 2008). Recently, the global warming scenario created interest in understanding the carbon storage of mangroves species. Despite accounted for only 2.4% of tropical forests (Spalding et al., 1997; Chmura et al., 2003), the capacity of this halophytic plant to store carbon is four times greater than most other tropical forests around the world (Daniel et al., 2011).

Indeed, mangrove forests are exceptional in their ability to store carbon. Their dense vegetation, intricate root systems, and the anaerobic conditions of their waterlogged soils create ideal conditions for the accumulation and storage of organic matter, including carbon. As a result, mangrove forests are recognized as one of the most efficient ecosystems in terms of carbon sequestration and storage. Kauffman and Donato (2012) highlight the significance of mangrove forests in carbon storage, noting that mangrove carbon pools are among the highest of any forest type. Figure 4 in their study illustrates the substantial carbon stocks held within mangrove ecosystems compared to other forest types, underscoring the importance of recognizing and conserving mangroves for their role in climate change mitigation.

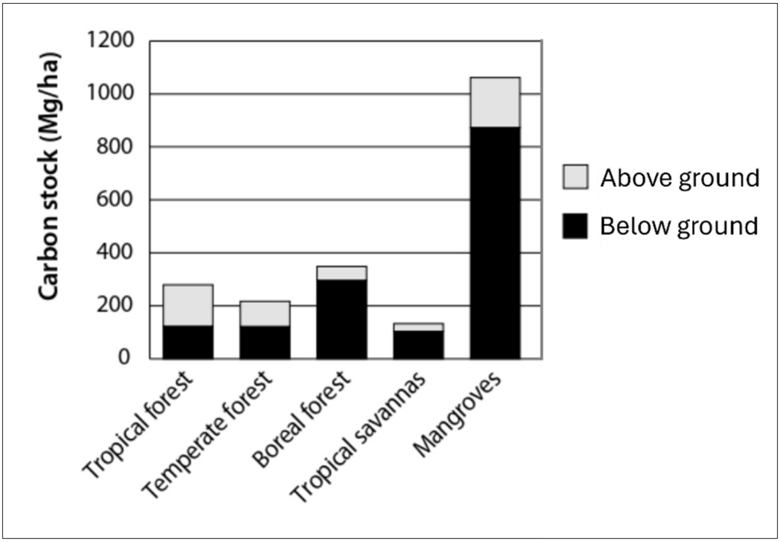

Figure 4: Total ecosystem carbon pools (above and below ground) for some major land cover types of the world (Kauffman and Donato, 2012).

Despite their ecological importance, mangrove forests have often been undervalued and subjected to degradation and loss due to factors such as coastal development, aquaculture, and deforestation. Recognizing the immense carbon storage capacity of mangroves can help elevate their conservation status and promote sustainable management practices to preserve these critical ecosystems for both climate mitigation and biodiversity conservation.

Tengku Mohd Hashim et al. (2015) studied mangrove profile in terms of species composition, diameter sizes, BA and AGB estimates in Merbok, Kedah, Malaysia. Four species of mangroves are present in the study area namely *Rhizophora apiculata* (Bakau minyak), *Bruguiera parvifolia* (Lenggadai), *B. gymnorrhiza* (Tumu merah) and *Avicennia marina* (Api-api putih). *B. parvifolia* is the most dominant with a density of 444 trees ha^{-1},