

Assessment of Carbon Sequestration of Natural Mixed Forest and Plantation Forests of Pine of Langol Hill, Imphal-West District, Manipur, India

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ABSTRACT

This research studies the carbon sequestration in two forest types: Mixed natural forests (Site I) and *Pinus kesiya* plantations (Site II). Tree diameter at breast height (DBH) and heights were measured across various quadrats, and carbon storage was estimated using allometric equations for different diameter classes. Site I had higher tree density (1240 plants ha⁻¹) but lower biomass (7179.51 kg ha⁻¹) and carbon content (3589.75 kg ha⁻¹) than Site II, which had 980 plants ha⁻¹, 36951.25 kg ha⁻¹ biomass, and 18475.61 kg ha⁻¹

carbon content. And the total carbon sequestered by all the trees in Site I and Site II were found to be 13.16 Tons Ha⁻¹ Yr⁻¹ and 67.74 Tons Ha⁻¹ Yr⁻¹ respectively. Results indicate that despite Site I's density, its younger, smaller trees store less carbon than the older, larger trees in Site II. This highlights the critical role of forest age and species composition in carbon sequestration assessments, with implications for forest management and climate mitigation strategies.

Keywords Natural mixed forests, *Pinus kesiya* plantation forests, Diameter at breast height (DBH), Allometric equation, Carbon sequestration.

INTRODUCTION

Forests serve as the major carbon pool and have the potential to store carbon, which helps mitigate climate change (Brown *et al.* 1996). It also acts as the “sinks” for the greenhouse gases (Eggleston *et al.* 2006, Eriksson and Berg 2007). Forest ecosystem plays a crucial role in storing over 80% of terrestrial above-ground carbon and more than 70% of soil organic carbon (Six *et al.* 2002). Tropical forests are vital in lowering atmospheric carbon (Devi and Yadava 2015), and natural forests are known to store carbon for extended periods, surpassing plantations and agroforestry systems. Anthropogenic activities have been one of the major sources of carbon emissions, with international accords like the Kyoto Protocol emphasizing mitigation of carbon emissions (Yum-

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nam and Dey 2022), and urging continued research on biosphere carbon sequestration to combat rising greenhouse gases (Navarro-Cerrillo *et al.* 2022). Reforestation, afforestation, and forest conservation serve as the sinks for carbon (Baishya *et al.* 2009). Afforestation of degraded areas or wastelands improves soil organic constituents (Bárcena T. G. *et al.* 2014, Palmero-Iniesta *et al.* 2021). Degraded areas hold great potential for effectively sequestering carbon within the soil (Lal 2001), presenting a significant opportunity to mitigate climate change.

Forest plantations have been widely promoted as a proactive strategy to sequester carbon from the atmosphere, reducing the detrimental effects of climate change (Liao *et al.* 2010). Plantations can restore land, protect soil, store carbon, conserve water, and reduce poverty by providing social and economic benefits, especially in developing countries (Avtar *et al.* 2014). Plantation forests play a significant role in carbon storage across ecosystems (Teerawong *et al.* 2012). The importance of plantations in addressing climate change depends on how efficiently they absorb carbon, and this rate is crucial for evaluating their impact and calculating carbon credits, which reflect their effectiveness in climate mitigation (Avtar *et al.* 2014). Plantation forests store large amounts of carbon, with accumulation depending mainly on different diameter classes, where the mature diameter classes store the most (Dabi *et al.* 2021, Pant and Tewari 2013). In many cases, Pines are a preferred choice for afforestation, particularly in arid and semi-arid regions, due to their rapid growth and remarkable adaptability to diverse soil types (Vadell *et al.* 2016). Navarro-Cerrillo *et al.* (2022) stated that high-intensity thinning helped *Pinus stands* for rapid growth, leading to a higher potential for sequestering carbon. Moreover, different scientists have shown that higher accumulation of biomass was found in mature tree stands compared to younger stands. Justine *et al.* (2015) showed that older *Pinus massoniana* plantations accumulate biomass faster than younger ones, making stand age a key factor in enhancing carbon sequestration. Also, in the case of *Pinus roxburghii*, Pant and Tewari (2013) showed that mature stands accumulated more biomass.

Therefore, there is an essential need to decrease

the ever-emerging disturbances on forests, thereby reducing greenhouse gas emissions. Given the functioning of a plantation forest and natural mixed forests regarding their natural carbon-sequestering potential, the present study emphasizes assessing the potential rate of carbon sequestration of natural mixed forests and plantation forests of Pine of Langol Hill, Imphal-West District, Manipur, India.

MATERIALS AND METHODS

The present study was conducted in natural mixed forests (Site I) and plantation forests (Site II) of Langol Hill, Imphal-West District, Manipur, India, under the Langol reserve forest. The forest sites cover 1 ha in area. However, Forest Site I is located between 24°49'53"N and 93°53'13"E with an elevation ranging from 800 m to 927 m above sea level, while Forest Site II is located between 24°50'51"N and 93°52'53"E with an elevation of 1050 m above sea level. The study area is adjacent to Lamdeng village on the West, Lamshang village on the South, Heingang on the East and Kameng village and Luwangshangbam village on the Northwest and North, respectively.

The Langol Hill range has an altitude range from 600 m to 1050 m above sea level. In general, the climate of the study area falls under a subtropical humid climate, with an average annual rainfall of 1259 mm. Temperature ranges from 0°C to 36°C. The soil of the area is clayey loam soil, having a pH ranging from 4.3 to 5. The color of the soil is red.

The measurement of biomass of these tree species is determined by considering the diameter at breast height of the trees using the allometric equation given by Brown (1997) of wet forests. Biomass is measured in kg ha⁻¹. The equation is given as:

$$\text{Biomass} = 21.297 - (6.953 \times \text{DBH}) + 0.740 \times (\text{DBH})^2$$

Where DBH is the diameter at breast height.

The calculation of carbon content adhered to the widely accepted estimation that carbon storage constitutes approximately 50% of the dry biomass (Brown 1997, Beets *et al.* 2012, Penman *et al.* 2003,

Ravindranath and Ostwald 2008).

Carbon sequestration is computed by calculating the CO₂ weight, based on its composition of one carbon and two oxygen atoms. With atomic weights of 12.00115 for carbon and 15.9994 for oxygen, the molecular weight of CO₂ is 43.999915. The ratio of CO₂ to carbon is therefore $43.999915 \div 12.00115 = 3.6663$. To find the weight of carbon dioxide stored in a tree, the weight of carbon in the tree is multiplied by 3.6663 (Prasadan P. K. and Jithila P. J. 2018, Toochi 2018).

RESULTS AND DISCUSSION

Results for Forest site I

In this study, Forest Site I exhibited a diverse composition of tree species belonging to varied families, which included *Bombax ceiba*, *Castanopsis hystrix*, *Celtis cinnamomea*, *Gmelina arborrea*, *Litsaea poly-*

antha, *Quercus serratus*, *Santalum album*, *Schima wallichii*, *Spondias Mangifera*, *Terminalia citrina*, *Terminalia myriocarpa* and *Toona ciliata* (Table 1). Among these, *Schima wallichii* showed as the most predominant species in Forest Site I, marking its importance in the ecosystem. These tree species were important to local communities, providing essential fuelwood for cooking, heating and making agricultural tools. Several tree species in Forest Site I are utilized in traditional medicine by local communities, serving as natural remedies for a variety of health conditions.

It was observed that the highest density of trees with 520 plants ha⁻¹ was found in diameter 20–40 cm diameter class, and the lowest was found in the 80–100 cm diameter class with 90 plants ha⁻¹. *Quercus serratus* species exhibited the lowest diameter at the breast height (DBH), measuring 17 cm (0–20 diameter class), and the highest diameter belonged to *Bombax ceiba*, having 86 cm (80–100 diameter

Table 1. Species-wise carbon content and carbon sequestered for Forest Site I. Source: The Authors.

Species name	Family name	Girth class (cm)	Tree density (plant ha ⁻¹)	Biomass (kg ha ⁻¹)	Carbon content (kg ha ⁻¹)	Carbon sequestered (kg ha ⁻¹ yr ⁻¹)	Carbon sequestered (tons ha ⁻¹ yr ⁻¹)
<i>Bombax ceiba</i>	Malvaceae	60-80	20	2552.78	1276.39	4679.63	4.68
		80-100	10	3859.62	1929.81	7075.26	7.08
Total				3206.2	1603.1	5877.45	5.88
<i>Castanopsis hystrix</i>	Fagaceae	40-60	50	863.33	431.67	1582.61	1.58
		60-80	20	2227.06	1113.53	4082.54	4.08
		80-100	10	3343.64	1671.82	6129.39	6.13
Total			2144.68	1072.34	3931.51	3.93	
<i>Celtis cinnamomea</i>	Cannabaceae	40-60	30	1126.62	563.31	2065.26	2.07
<i>Gmelina arborrea</i>	Lamiaceae	40-60	20	531.1	265.55	973.59	0.97
		60-80	40	2346.95	1173.48	4302.31	4.30
		80-100	40	3418.78	1709.39	6267.14	6.27
Total			2098.94	1049.47	3847.68	3.85	
<i>Litsaea polyantha</i>	Lauraceae	0-20	40	65.35	32.68	119.8	0.12
		20-40	160	244	122	447.29	0.45
		40-60	20	606.9	303.45	1112.54	1.11
Total			305.42	152.71	559.87	0.56	
<i>Quercus serratus</i>	Fagaceae	0-20	10	53.44	26.72	97.96	0.10
		20-40	50	263.93	131.97	483.82	0.48
		40-60	40	1226.72	613.36	2248.76	2.25
		60-80	50	2590.87	1295.44	4749.45	4.75
		80-100	30	3478.73	1739.37	6377.03	6.38
		Total			1522.74	761.37	2791.41

Table 1. Continued.

Species name	Family name	Girth class (cm)	Tree density (plant ha ⁻¹)	Biomass (kg ha ⁻¹)	Carbon content (kg ha ⁻¹)	Carbon sequestered (kg ha ⁻¹ yr ⁻¹)	Carbon sequestered (tons ha ⁻¹ yr ⁻¹)
<i>Santalum album</i>	Santalaceae	0-20	20	66.75	33.38	122.36	0.12
		20-40	60	297.14	148.57	544.7	0.54
Total				181.95	90.97	333.53	0.33
<i>Schima wallichii</i>	Theaceae	0-20	50	64.92	32.46	119.01	0.12
		20-40	220	238.79	119.4	437.74	0.44
		40-60	40	797.9	398.95	1462.67	1.46
Total				367.2	183.6	673.14	0.67
<i>Spondias mangifera</i>	Anacardiaceae	40-60	30	1058.45	529.23	1940.3	1.94
<i>Terminalia citrina</i>	Combretaceae	40-60	10	1035.81	517.91	1898.8	1.90
		60-80	10	1725.15	862.58	3162.46	3.16
Total				1380.48	690.24	2530.63	2.53
<i>Terminalia myriocarpa</i>	Combretaceae	40-60	20	833.17	416.59	1527.33	1.53
<i>Toona ciliata</i>	Meliaceae	20-40	30	146.99	73.5	269.45	0.27
		60-80	50	1113.71	556.86	2041.6	2.04
		80-100	60	2526.45	1263.23	4631.36	4.63
Total				1262.38	631.19	2314.14	2.31

class) (Table 1).

The total tree density in all the diameter classes was found to be 1240 plants ha⁻¹, reflecting the abundance and variety of tree species in forest Site I. *Schima wallichii* was found to be the dominant species in their developing stages, having the highest tree density among all the species, with tree density of 310 plants ha⁻¹ (Table 1). This finding underlines the ecological significance of *Schima wallichii* within

the forest. However, *Terminalia citrina* and *T. myriocarpa* were found with the lowest tree density, each accounting for 20 plants ha⁻¹ (Table 1).

Quercus serratus exhibited the highest rate of carbon sequestration, having 2791.41 kg ha⁻¹yr⁻¹ (Fig. 1). It may be due to the second-highest tree density and the bigger DBH as compared to other tree species with the highest tree density. *Gmelina arborea* trees were found to be in their developing stages, hence

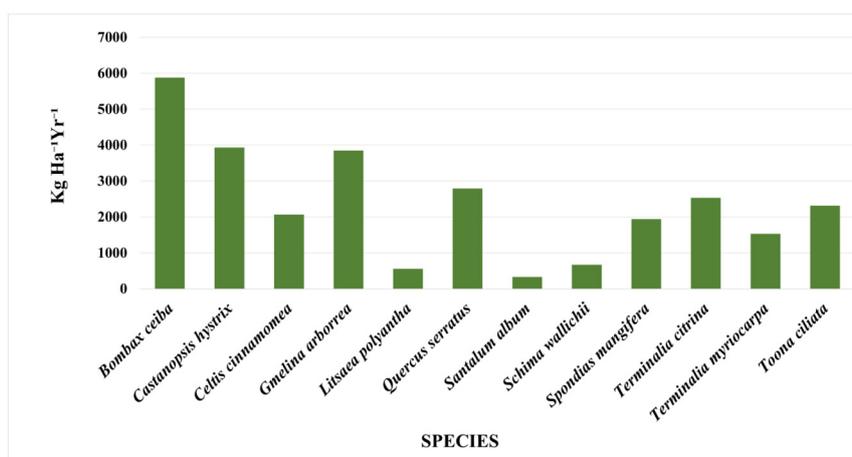


Fig. 1. Annual carbon sequestration at Site I.

Table 2. Total biomass, carbon content and carbon sequestration of Forest Site I. Source: The Authors.

Girth class (cm)	Tree density (plant ha ⁻¹)	Biomass (kg ha ⁻¹)	Carbon content (kg ha ⁻¹)	Carbon sequestered by all trees (kg ha ⁻¹ yr ⁻¹)	Carbon sequestered by all trees (Tons ha ⁻¹ yr ⁻¹)
0-20	120	64.41	32.21	118.09	0.12
20-40	520	244.25	122.12	447.73	0.45
40-60	310	952.17	476.08	1745.45	1.75
60-80	200	2439.28	1219.64	4471.57	4.47
80-100	90	3479.4	1739.7	6378.26	6.38
Total	1240	7179.51	3589.75	13161.1	13.16

their DBH has the smallest range (Table 1). *Santalum album* has the lowest rate of carbon sequestration, having 333.33 kg ha⁻¹ yr⁻¹ (Fig. 1). It may be due to the lowest tree density and the smallest DBH. The present findings were similar to those reported by Vishnu and Patil (2017), who reported that *Swietenia mahagoni* sequestered 3,916.81 kg of CO₂ per tree due to its large DBH, while *Sesbania sesban* sequestered the least at 72.75 kg per tree, likely due to its smaller DBH of 0.148 meters. The estimated total amount of biomass, carbon content, and rate of carbon sequestered were found to be 7179.51 kg ha⁻¹, 3589.75 kg ha⁻¹, and 13161.10 kg⁻¹ ha⁻¹ yr⁻¹, respectively (Table 2).

Results for Forest Site II

Forest Site II was characterized as a plantation forest primarily consisting of *Pinus kesiya*, associated with *Acacia auriculiformis* and *Toona ciliata* (Table 3).

The present plantation forest was approximately 30 years old. It was found to be in their mature stage, with some trees in their late developing stage. In this forest site, 80–100 diameter class has the highest concentration of tree density, having 350 plants ha⁻¹, and the lowest concentration was found to be under 40–60 cm, 120–140 cm and 140–160 cm diameter class having tree density of 50 plants ha⁻¹ (Table 3). The highest diameter at breast height was found to be 153 cm (140–160 cm diameter class), which belonged to *Pinus kesiya* species. *Toona ciliata*, having a 52 cm (40–60 cm diameter class) diameter at breast height, was found to be the lowest diameter.

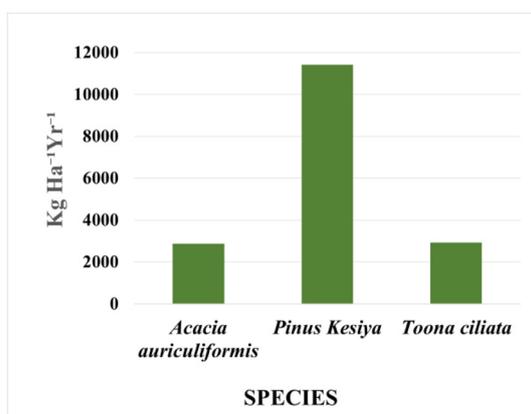
Within Forest Site II, the total tree density was estimated to be 980 plants ha⁻¹. The dominant species, *Pinus kesiya*, exhibited the highest tree density of 900 plants ha⁻¹. In contrast, *Acacia auriculiformis* had the lowest tree density among the species, with 20 plants ha⁻¹. *Pinus kesiya* had the highest carbon sequestra-

Table 3. Species-wise carbon content and carbon sequestered of Forest Site II. Source: The Authors.

Species name	Family name	Girth class (cm)	Tree density (plant ha ⁻¹)	Biomass (kg ha ⁻¹)	Carbon content (kg ha ⁻¹)	Carbon sequestered (kg ha ⁻¹ yr ⁻¹)	Carbon Sequestered (tons ha ⁻¹ yr ⁻¹)
<i>Acacia auriculiformis</i>	Fabaceae	40-60	10	1265.46	632.73	2319.78	2.32
		60-80	10	1870	935	3427.99	3.43
Total				1567.73	783.87	2873.88	2.87
<i>Pinus Kesiya</i>	Pinaceae	40-60	10	1586.31	793.16	2907.94	2.91
		60-80	160	2691.32	1345.66	4933.59	4.93
		80-100	350	4261.83	2130.92	7812.57	7.81
		100-120	280	6380.79	3190.4	11696.95	11.70
		120-140	50	9441.57	4720.79	17307.81	17.31
		140-160	50	12997.12	6498.56	23825.67	23.83
Total				6226.49	3113.25	11414.09	11.41
<i>Toona ciliata</i>	Meliaceae	40-60	30	1274.97	637.49	2337.21	2.34
		60-80	30	1920.28	960.14	3520.16	3.52
Total				1597.63	798.81	2928.69	2.93

Table 4. Total biomass, carbon content and carbon Sequestration of Forest Site II. Source: The Authors.

Girth class (cm)	Tree density (plant ha ⁻¹)	Biomass (kg ha ⁻¹)	Carbon content (kg ha ⁻¹)	Carbon sequestered by all trees (kg ha ⁻¹ yr ⁻¹)	Carbon sequestered by all trees (tons ha ⁻¹ yr ⁻¹)
0-20	0	0	0	0	0.00
20-40	0	0	0	0	0.00
40-60	50	1335.34	667.67	2447.88	2.45
60-80	200	2534.6	1267.3	4646.3	4.65
80-100	350	4261.83	2130.91	7812.56	7.81
100-120	280	6380.79	3190.39	11696.93	11.70
120-140	50	9441.57	4720.78	17307.8	17.31
140-160	50	12997.12	6498.56	23825.67	23.83
Total	980	36951.25	18475.61	67737.13	67.74

**Fig. 2.** Annual carbon sequestration at Site II.

tion rate, having 11414.09 kg ha⁻¹ yr⁻¹ (Fig. 2). This may be due to a higher diameter class as well as the highest number of tree density. The lowest carbon sequestration was found in *Acacia auriculiformis* with 2873.65 kg ha⁻¹ yr⁻¹ (Fig. 2). The total biomass was found to be 36951.25 Kg ha⁻¹, while the total calculated carbon content was found to be 18475.61 kg ha⁻¹. And total rate of carbon sequestered by this was found to be 67737.13 kg ha⁻¹ yr⁻¹. These figures showed that Forest Site II has much higher total biomass, total carbon content, and rate of carbon sequestration compared to Forest Site I (Table 4).

DISCUSSION

In Forest Site I, the presence of lower diameter classes (0-20cm), diameter class with DBH of 17 cm, marked a relatively youthful and developing forest. This may

be due to the degradation of the forests, mainly for anthropogenic purposes. However, through the realization of local communities about the importance of forest conservation and the implementation of initiatives like the National Afforestation Program, there has been a remarkable restoration of these previously degraded forests (Sadananda *et al.* 2022). Forest Site I has been categorized as a secondary forest. Secondary forests are regenerated naturally following human or natural disturbances, exhibiting distinct differences in structure and canopy species compared to nearby primary forests on similar sites (Chokkalingam and De Jong 2001). On the contrary, in Forest Site II, the trees have reached a mature stage, as evidenced by higher diameter classes of 140–160 diameter class. The maturation process has resulted in a higher overall biomass within this area, similar to the findings of West *et al.* (2014), resulting in higher carbon content and a higher rate of carbon sequestration compared to Forest Site I. This is due to higher diameter classes and mature trees found in Forest Site II as compared to Forest Site I. The present findings were similar to Devi and Yadava (2015), demonstrating that a greater DBH corresponds to higher tree biomass, indicating a positive correlation between the DBH of tree species and their biomass components.

Forest Site II, dominated by *Pinus kesiya* trees, exhibited a higher diameter at Breast Height (DBH) reaching up to 153 cm. These trees fall within the diameter class of 140–160 cm, highlighting their size and maturity. This is attributed to the plantation's age of approximately 30 years, enabling the pine trees to grow substantially, consistent with findings by Li *et*

al. 2011 on Korean Pine (*Pinus koraiensis*) forest. Justine *et al.* (2015) recorded that the plantation of *Pinus massoniana* forest increased biomass as the stand ages progressed, exhibiting that stand age plays a major variable role for ecosystem carbon sequestration. Moreover, the Pine tree species is a fast-growing tree species and has high adaptability to any soil type (Vadell *et al.* 2016). However, some trees were observed in their late developmental stage, indicating ongoing growth and regeneration within the forest ecosystem. This complex mix of age and development stages adds to the overall biodiversity and ecological dynamics of Forest Site II.

The total tree density was found to be higher in Forest Site I, with a density of 1240 plants ha⁻¹ as compared to 980 plants ha⁻¹ in Forest Site II. This clearly showed that despite higher biomass obtained from Forest Site II, the maximum tree density was found in Forest Site I. One reason is that the diameter classes in the case of Forest Site I are much smaller due to their secondary forests in nature, as compared to Forest Site II, where the tree sizes were found to be higher in diameter size, and the age factor also plays major role for higher rate of storing carbon. Köhl *et al.* (2017) showed that old-growth trees in tropical forests maintain high rates of carbon accumulation later in life, in addition to their long carbon resistance times, contributing to carbon stocks. In the present study higher rate of carbon sequestration was recorded in Forest Site II. The forest Site I trees in the near future will have a higher tendency of producing higher biomass, which in turn will have higher carbon density, as Stephenson *et al.* (2014) determined that biomass continuously increases with tree size.

CONCLUSION

It is obvious that the accumulation of carbon by larger trees with height, age, and larger diameter classes contributes more than by trees with lower diameter classes and age. It also shows that the young mixed natural tree forests have a great potential to sequester carbon, which, when they mature. Plantation forests of *Pinus kesiya*, which were found mature, showed a great deal of accumulation of carbon stock, which is the most intricate factor for ecosystem conservation. Plantation forests exhibit higher carbon storage and

sequestration gives higher annual productivity (Lal and Singh 2000, Köhl *et al.* 2017). Therefore, both the plantation forests and young natural forests plays a vital role in carbon sequestration thereby mitigating climate change.

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