Quantifying the Impact of Tree Species Diversity on Carbon Sequestration Insight of Two-Decade Plantation

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Abstract

Forest plantations play a crucial role in combating climate change by acting as carbon sinks and supporting carbon trading initiatives. This study investigates carbon sequestration in two age classes 4 years and 20 years of six tree species at Pakistan Forest Institute: Bombax ceiba, Dalbergia sissoo, Eucalyptus camaldulensis, Morus alba, Paulownia fortune , and Populus deltoides. Data on DBH and height were used with species-specific allometric equations to estimate above- and below-ground biomass. Eucalyptus camaldulensis showed the highest carbon sequestration, storing 1,027 kg at 20 years (0.127 tons/year) versus only 6.7 kg at 4 years. Populus deltoides also showed strong performance with 471 kg at 20 years. ANOVA and correlation analysis confirmed a strong positive association between tree size, age, and carbon accumulation ($p < 0.001$). The study underscores the need for species-specific planning and long-term plantation maturity to optimize sequestration outcomes. These findings have implications for afforestation and REDD+ initiatives in Pakistan, offering a scientific foundation for sustainable forest management strategies.

Keywords: Carbon Sequestration, Tree Age, Biomass, Carbon Trading, Afforestation, Reforestation, Sustainable Forest Management, Climate Change Mitigation.

Introduction

Climate change remains one of the most pressing global challenges of the 21st century. It is primarily driven by anthropogenic greenhouse gas (GHG) emissions originating from fossil fuel combustion, deforestation, and unsustainable land use practices. The consequences extend beyond environmental degradation, threatening food security, public health, and economic stability worldwide. According to the Intergovernmental Panel on Climate Change (IPCC), the global average temperature has already risen by 0.87°C between 1850 and 2016 and could increase by up to 6.0°C by the end of the century if current emission trends continue (Masson-Delmotte et al., 2022).

Among all GHGs, carbon dioxide (CO_2) is the most prevalent, accounting for nearly 76% of global GHG emissions. Natural carbon sinks such as forests, oceans, and soil play a vital role in offsetting these emissions. Forest ecosystems absorb approximately 2.6 billion tons of CO_2 per year, making them one of the most effective nature-based solutions for climate change mitigation (FAO, 2020).

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Planted forests, although comprising just 7% of global forest cover, supply more than 35% of the world's industrial roundwood and sequester a significant portion of atmospheric carbon. Their expansion is particularly valuable in countries like Pakistan, where forest cover is alarmingly low at 5.1%, compared to the global average of 31% (Bukhari et al., 2012) Additionally, Pakistan faces a deforestation rate of approximately 27,000 hectares annually, highlighting the urgency for afforestation and reforestation initiatives (Irshad et al., 2016)

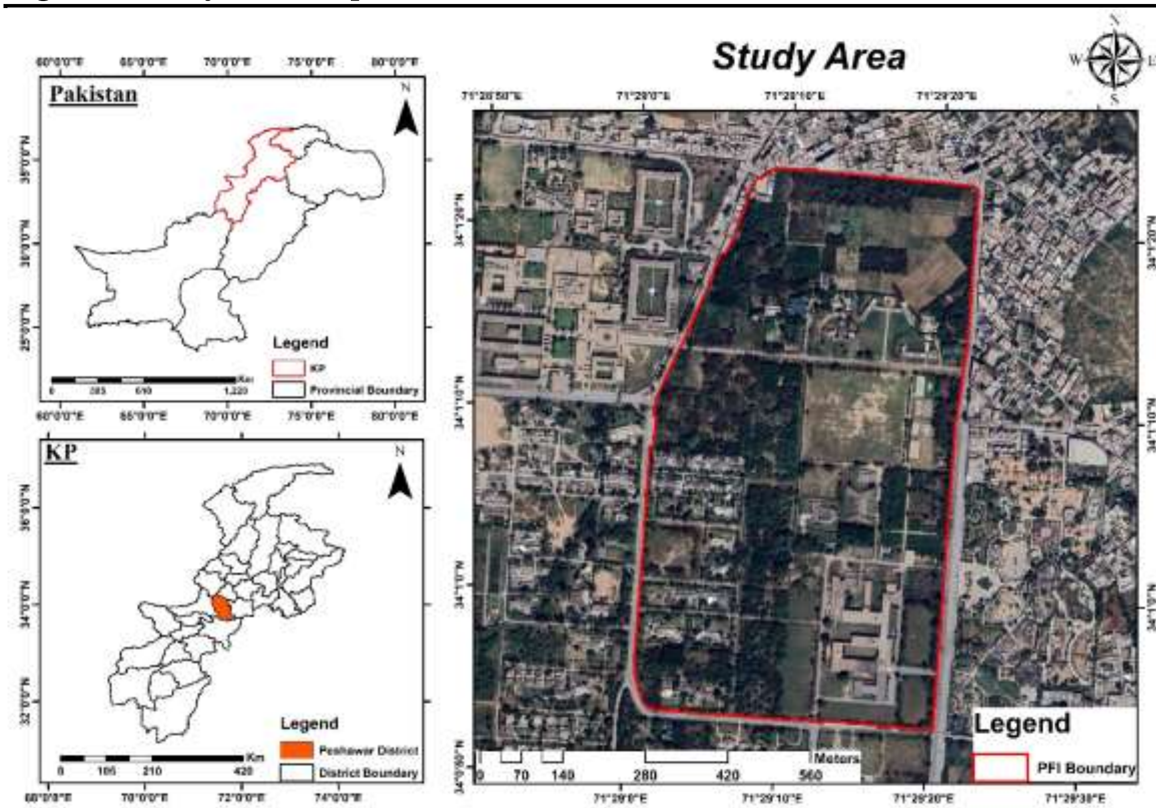
In this context, plantation forestry emerges as a scalable and cost-effective strategy not only for enhancing carbon sequestration but also for restoring degraded ecosystems and supporting rural livelihoods. With appropriate species selection, plantation design, and site management, forest plantations can contribute significantly to global mitigation targets and national efforts under frameworks such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) (Kelly, 2017).

This study aims to quantify the impact of tree age and species diversity on carbon sequestration by comparing two age classes—4 years and 20 years—across six tree species commonly cultivated in Pakistan. The findings are intended to inform future afforestation efforts, improve carbon stock estimation models, and support policy decisions for sustainable forest management and climate action

Study Area

Peshawar District, part of Khyber Pakhtunkhwa's Peshawar Division, lies approximately 160 km west of Islamabad. Its administrative center, Peshawar city, also serves as the provincial capital. Geographically, it is situated around 34.02°N latitude and 71.56°E longitude, with an elevation of about 331 meters above sea level. The district spans roughly 1,257 square kilometers.

Figure 1: Study Area Map



Materials and Methods

Data Collection and Measurement Procedures

Data on tree diameter at breast height (DBH) and tree height were collected using standardized forestry measurement tools to ensure accuracy and consistency. Vernier calipers were employed to measure the DBH of smaller trees and saplings with precision, while a diameter tape was used for larger trees. In both cases, measurements were taken at a uniform height of 1.3 meters above the ground. To enhance reliability, multiple readings were taken for each tree, and the average was recorded. Tree height was determined using a clinometer, which involved measuring the angle to the tree's apex from a known horizontal distance. The actual height was then calculated using the trigonometric formula: Height = Horizontal Distance × tan(Angle).

Methodology

Field data were collected from a 20-year-old plantation located within the study area. For comparative purposes, data from a 4-year-old plantation were obtained from an official annual progress report. Both DBH and height measurements were used to estimate biomass using species-specific allometric equations. The calculated above-ground biomass (AGB) was then multiplied by 0.47 to estimate above-ground carbon (AGC). To estimate below-ground biomass (BGB), a multiplication factor of 0.44 was applied to the AGB. This methodology allowed for a systematic comparison of carbon sequestration potential across different plantation ages.

Table 1: Specie equation and source

Specie	Allometric equation	Source
Populus deltoids	AGM=0.0194*(D^2*H)^0.9654	(Ali et al., 2020)
Paulownia fortune	AGM=0.0165*(D^2*H)^0.9969	(Ali et al., 2020)
Eucalyptus camaldulensis	AGM=0.023*(D^2*H)^0.9985	(Ali et al., 2020)
Others	AGM=0.0112(ƒD^2H)^0.916	(Chave et al., 2005)

Results and Discussion

Table 2: Descriptive summary of different species, i.e., *Bombax ceiba, Dalbergia sissoo, Eucalyptus camaldulensis, Morus alba, Paulownia fortunei and Populus deltoids* of two age classes 4 &20

	Species	Age	Dia (cm)	Height (m)	AGB kgs	Carbon Stock kgs	BGB kgs	Carbon Stock kgs2	Total Carbon	Total Carbon in tnn	Carbon Seques-tration	Carbon Seques-tration per year
N	Bombax Ceiba	20	20	20	20	20	20	20	20	20	20	20
	Bombax Ceiba	12	12	12	12	12	12	12	12	12	12	12
	Dalbergia sissoo	20	20	20	20	20	20	20	20	20	20	20
	Dalbergia sissoo	25	25	25	25	25	25	25	25	25	25	25
	Eucalyptus camaldulensis	86	86	86	86	86	86	86	86	86	86	86
	Morus Alba	44	44	44	44	44	44	44	44	44	44	44
	Morus alba	20	20	20	20	20	20	20	20	20	20	20
	Paulownia fortune	34	34	34	34	34	34	34	34	34	34	34

	Populus deltoids	26	26	26	26	26	26	26	26	26	26	26
Mean	Bombax Ceiba	4.00	8.04	4.02	0.664	0.312	0.292	0.137	0.449	4.49e-4	0.00164	4.11e-4
	Bombax Ceiba	20.0	31.3	16.5	30.5	14.3	13.4	6.30	20.6	0.0206	0.0755	0.00378
	Dalbergia sissoo	4.00	10.0	8.16	4.44	2.09	1.96	0.919	3.01	0.00301	0.0110	0.00275
	Dalbergia sissoo	20.0	14.9	12.4	18.3	8.62	8.07	3.79	12.4	0.0124	0.0454	0.00227
	Eucalyptus camaldulensis	16.3	19.1	15.8	201	94.3	88.3	41.5	136	0.136	0.497	0.0283
	Morus Alba	20.0	16.7	10.7	17.0	8.01	7.50	3.52	11.5	0.0115	0.0422	0.00211
	Morus alba	4.00	6.04	5.68	1.06	0.498	0.466	0.219	0.717	7.17e-4	0.00262	6.56e-4
	Paulownia fortune	10.6	13.3	8.03	31.3	14.7	13.8	6.47	21.2	0.0212	0.0775	0.00657
	Populus deltoids	7.69	12.5	8.75	54.8	25.8	24.1	11.3	37.1	0.0371	0.136	0.00876
Standard deviation	Bombax Ceiba	0.00	0.449	0.540	0.125	0.0588	0.0551	0.0259	0.0847	8.47e-5	3.10e-4	7.75e-5
	Bombax Ceiba	0.00	5.31	2.35	11.7	5.50	5.15	2.42	7.92	0.00792	0.0290	0.00145
	Dalbergia sissoo	0.00	0.895	0.531	0.787	0.370	0.346	0.163	0.533	5.33e-4	0.00195	4.87e-4
	Dalbergia sissoo	0.00	7.09	4.64	17.7	8.33	7.80	3.67	12.0	0.0120	0.0439	0.00220
	Eucalyptus camaldulensis	6.80	9.41	5.37	233	109	102	48.1	157	0.157	0.576	0.0269
	Species	Age	Dia (cm)	Height (m)	AGB kgs	Carbon Stock kgs	BGB kgs	Carbon Stock kgs2	Total Carbon	Total Carbon tnn	Carbon inSeques-tration	Carbon Seques-tration per year
	Morus Alba	0.00	8.04	4.94	20.0	9.40	8.80	4.14	13.5	0.0135	0.0495	0.00248
	Morus alba	0.00	0.374	0.251	0.137	0.0642	0.0601	0.0282	0.0924	9.24e-5	3.38e-4	8.46e-5
	Paulownia fortune	7.99	5.71	1.86	35.3	16.6	15.5	7.30	23.9	0.0239	0.0874	0.00307
	Populus deltoids	6.87	10.6	4.02	108	50.8	47.6	22.4	73.2	0.0732	0.268	0.0125
Minimum	Bombax Ceiba	4	7.43	3.01	0.459	0.216	0.202	0.0950	0.311	3.11e-4	0.00114	2.85e-4
	Bombax Ceiba	20	21.0	12.0	12.0	5.66	5.29	2.49	8.14	0.00814	0.0298	0.00149
	Dalbergia sissoo	4	9.11	6.50	3.47	1.63	1.52	0.717	2.35	0.00235	0.00858	0.00215
	Dalbergia sissoo	20	3.00	3.00	0.193	0.0908	0.0851	0.0400	0.131	1.31e-4	4.79e-4	2.39e-5
	Eucalyptus camaldulensis	4	6.00	6.00	6.70	3.15	2.95	1.39	4.54	0.00454	0.0166	8.30e-4
	Morus Alba	20	5.00	3.00	0.416	0.196	0.183	0.0860	0.282	2.82e-4	0.00103	5.15e-5
	Morus alba	4	5.63	5.19	0.896	0.421	0.394	0.185	0.607	6.07e-4	0.00222	5.55e-4

	Paulownia fortune	4	8.22	5.00	8.04	3.78	3.54	1.66	5.44	0.00544	0.0199	0.00256
	Populus deltoids	4	6.56	6.19	4.69	2.21	2.07	0.971	3.18	0.00318	0.0116	0.00291
Maximum	Bombax Ceiba	4	8.91	4.87	0.859	0.404	0.378	0.178	0.581	5.81e-4	0.00213	5.32e-4
	Bombax Ceiba	20	37.0	19.0	44.9	21.1	19.8	9.29	30.4	0.0304	0.111	0.00556
	Dalbegia sissoo	4	12.0	8.91	6.31	2.96	2.77	1.30	4.27	0.00427	0.0156	0.00390
	Dalbergia sissoo	20	30.0	20.0	71.2	33.5	31.3	14.7	48.2	0.0482	0.176	0.00882
	Eucalyptus camaldulensis	20	41.0	28.0	1027	483	452	212	695	0.695	2.54	0.127
	Morus Alba	20	37.0	30.0	103	48.3	45.2	21.3	69.6	0.0696	0.255	0.0127
	Morus alba	4	6.91	6.02	1.38	0.648	0.607	0.285	0.933	9.33e-4	0.00341	8.54e-4
	Paulownia fortune	20	28.0	14.0	138	65.0	60.9	28.6	93.6	0.0936	0.343	0.0171
	Populus deltoids	20	44.0	18.0	471	221	207	97.4	319	0.319	1.17	0.0583

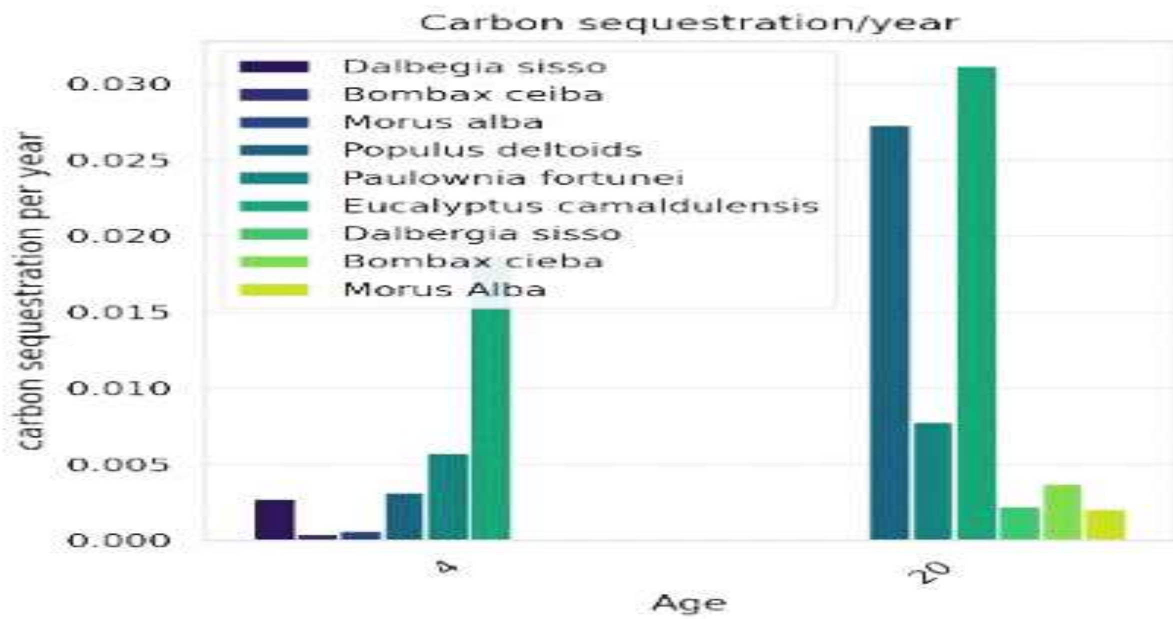
The overall observation shows height, DBH, above-ground biomass, below-ground biomass, carbon stock, total carbon, and carbon sequestration annually of six different species of 2 different age classes, i.e. 4 years, 20 years. The table shows a change (increase) in the DBH and height, the DBH and height second age class (20) is higher than the first age class, which is directly proportional to the carbon sequestered total and the sequestration annually.

Comparison of Age and Carbon Sequestration per Year

Carbon sequestration per year exhibits significant variation among different tree species across age classes. After 4 years, Eucalyptus demonstrates the highest annual carbon sequestration at 0.018, followed by *Paulownia fortunei* at approximately 0.007 per year. Dalbergia sissoo accumulates around 0.0003 annually, while *Populus deltoides* records a mean annual carbon sequestration of 0.003. For *Bombax ceiba*, the yearly sequestration rate is 0.0001, and for *Morus alba*, it is 0.0002, as illustrated in Table 1 and Figure 2.

In the 20-year class, Eucalyptus continues to lead with the highest mean carbon sequestration per year at 0.031, followed by *Populus deltoides* with 0.02 per year. Paulownia follows with an annual carbon sequestration of 0.007. *Bombax ceiba* records 0.0027 per year, while Dalbergia *sissoo* and *Morus alba* have mean annual sequestration rates of 0.0022 and 0.002, respectively, as presented in Table 1 and Figure 2.

Figure 2: Comparisn of Age and carbon sequestration per year of different tree species for two age classes



Analysis of Variance (ANOVA)

Table 3: Analysis of Variance (ANOVA) Results for Diameter, Height, Biomass, and Carbon Sequestration Parameters"

Source of variance	F	df1	df2	P
Dia(cm)	116.0	8	85.1	< .001
Height(m)	153.7	8	83.9	< .001
AGB kgs	86.3	8	84.3	< .001
Carbon stock kgs	86.3	8	84.3	< .001
BGB kgs	86.3	8	84.3	< .001
Carbon stock kgs (2)	86.3	8	84.3	< .001
total carbon	86.3	8	84.3	< .001
total carbon in tnn	86.3	8	84.3	< .001
Carbon sequestration	86.3	8	84.3	< .001
carbon sequestration per year	98.3	8	84.3	< .001

The ANOVA results reveal statistically significant differences among the six tree species across all measured parameters, including diameter at breast height (DBH), height, above-ground biomass (AGB), below-ground biomass (BGB), total carbon stock, and annual carbon sequestration. The F-values were notably high, for example, DBH (F = 116.0) and height (F = 153.7)—indicating substantial variation between species relative to within-species variation. Biomass and carbon-related parameters also showed strong differences, with F-values around 86.3. All associated p-values were less than 0.001, confirming that the observed interspecific differences are highly statistically significant. These results underscore the importance of species selection in maximizing growth and carbon sequestration potential in plantation forestry.

Correlation between Different Variables

The correlation matrix analysis examined the relationships between different variables, including age, diameter at breast height (Dia), height, above-ground biomass (AGB), below-ground biomass (BGB), total carbon stock, and carbon sequestration per year.

Table 4: correlation between different variables of different species for two age classes

	Age	Dia(cm)	Height(m)	AGB kgs	Carbon stock kgs	BGB kgs	Carbon stock kgs (2)	Total carbon	Total carbon in tnn	Carbon sequestration	carbon sequestration per year
Age	—										
Dia(cm)	0.625***	—									
Height(m)	0.614***	0.808 ***	—								
AGB kgs	0.360***	0.696 ***	0.724***	—							
Carbon stock kgs	0.360***	0.696 ***	0.724***	1.000 ***	—						
BGB kgs	0.360***	0.696 ***	0.724***	1.000 ***	1.000 ***	—					
Carbon stock kgs (2)	0.360***	0.696 ***	0.724***	1.000 ***	1.000 ***	1.000 ***	—				
Total carbon	0.360***	0.696 ***	0.724***	1.000 ***	1.000 ***	1.000 ***	1.000 ***	—			
Total carbon in tnn	0.360***	0.696 ***	0.724***	1.000 ***	1.000 ***	1.000 ***	1.000 ***	1.000 ***	—		
Carbon sequestration	0.360***	0.696 ***	0.724***	1.000 ***	1.000 ***	1.000 ***	1.000 ***	1.000 ***	1.000 ***	—	
Carbon sequestration per year	0.256***	0.652 ***	0.703***	0.980 ***	0.980 ***	0.980 ***	0.980 ***	0.980 ***	0.980 ***	0.980***	—

Note: * p < .05, ** p < .01, *** p < .001

A strong positive correlation was observed between tree age and diameter at breast height ($r = 0.625$, $p < 0.001$), indicating that tree diameter increases with age. Diameter and height were also strongly correlated ($r = 0.808$, $p < 0.001$), showing that larger diameters are typically associated with taller trees. Above-ground biomass (AGB) correlated positively with both diameter ($r = 0.696$, $p < 0.001$) and height ($r = 0.724$, $p < 0.001$), suggesting that larger trees accumulate more biomass. Carbon stock was perfectly correlated with AGB and BGB ($r = 1.000$, $p < 0.001$), confirming that biomass directly reflects carbon storage. Annual carbon sequestration showed high correlations with diameter ($r = 0.652$), height ($r = 0.703$), and AGB ($r = 0.980$), emphasizing that larger, more mature trees are more efficient carbon sinks. These results highlight the critical role of tree age and size in enhancing carbon sequestration, offering valuable insights for sustainable forest management and climate mitigation strategies.

Discussion

Forests store carbon in five key pools: living biomass (above and below ground), deadwood, litter, understory vegetation, and soil organic carbon (SOC) (Woodbury, Smith, Heath, & Management, 2007). This study focused primarily on above-ground carbon (AGC) and below-ground carbon (BGC), both of which are critical for assessing the carbon sequestration potential of plantation ecosystems. AGC typically constitutes the largest fraction of forest carbon and is influenced by species-specific traits, stand age, and planting density. Meanwhile, BGC, stored in root biomass, contributes significantly to long-term carbon stability and soil health.

The results of this study revealed strong positive relationships between tree size parameters (diameter at breast height and height), age, and carbon accumulation. These findings are consistent with allometric scaling theory, which posits that tree biomass by extension, carbon stock is a predictable function of tree dimensions (Chave et al., 2005). The strong statistical correlations ($r > 0.9$ for several biomass-carbon parameters) affirm that as trees grow in size and age, their capacity to sequester carbon increases exponentially. This supports earlier work by (Clark, 2000), who emphasized the influence of structural traits on biomass variability in tropical forests.

Species-specific differences in carbon sequestration were also pronounced. Eucalyptus camaldulensis and Populus deltoides demonstrated significantly higher carbon storage potential than other species such as Bombax ceiba and Morus alba. This can be explained by the biomass allocation theory, which suggests that fast-growing species invest more in above-ground growth during early developmental stages, resulting in rapid biomass accumulation. Additionally, these species tend to have higher wood density and growth rates, contributing further to their sequestration performance (Anbarashan et al., 2020; Fang et al., 2014).

The role of planting density and age was also evident. The 20-year-old plantations stored significantly more carbon than 4-year-old stands across all species, emphasizing the importance of plantation maturity in maximizing carbon sequestration. This finding aligns with the growth-density hypothesis, which suggests that increased competition in dense stands leads to accelerated vertical growth and greater biomass accumulation, up to a certain threshold (Stoffberg et al., 2010).

From a practical perspective, these results validate the strategic importance of selecting high-performing species for afforestation projects aimed at climate change mitigation. While Eucalyptus and Populus species offer high short-term returns due to rapid growth, integrating slower growing but long-lived species can improve long-term sustainability and biodiversity. Moreover, plantation forestry in peri-urban and rural areas could serve dual purposes enhancing carbon sinks and improving community livelihoods.

The theoretical underpinnings of this study anchored in forest ecology, allometry, and resource allocation demonstrate that carbon sequestration is not merely a function of biomass, but of complex interactions among species traits, environmental conditions, and management practices. These insights are vital for optimizing forest carbon models, especially in countries like Pakistan where data on plantation dynamics are limited.

Conclusion

This study provides significant insights into the growth patterns, biomass accumulation, and carbon sequestration potential of various tree species in plantation ecosystems, focusing on the differences between young (4-year) and mature (20-year) stands. The findings highlight the importance of species selection, stand age, and planting density in maximizing carbon sequestration in forest ecosystems. In conclusion, this study underscores the complex interplay between species characteristics, growth patterns, and carbon sequestration potential in forest ecosystems. Eucalyptus camaldulensis, with its exceptional growth rate and biomass accumulation, stands out as a key species for carbon sequestration initiatives. However, including other species with different growth dynamics can enhance the long-term sustainability and carbon storage capacity of forest plantations. These insights are crucial for developing effective forest management strategies aimed at climate change mitigation and improving the carbon sequestration potential of forests.

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