

Research Article

Carbon Sequestration Potential of Plantation Forests in Essera District, Dawro Zone, South Western Region of Ethiopia

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Received 18 November 2024; Revised 2 September 2025; Accepted 12 September 2025

Academic Editor: Poorani Gurumalles

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The growing threat of climate change has heightened the importance of carbon sequestration in terrestrial ecosystems, particularly in plantation forests. This study assessed the carbon sequestration potential of two dominant plantation species *Eucalyptus camaldulensis* and *Cupressus lusitanica* in Essera District, South Western Ethiopia. Standard forest inventory techniques were used to estimate aboveground biomass and soil organic carbon. Results indicated that both species contribute substantially to ecosystem carbon storage, with *C. lusitanica* showing slightly higher potential. These findings highlight the role of plantation forestry in climate change mitigation and provide insights for regional carbon accounting and sustainable land-use planning.

Keywords: aboveground biomass; carbon sequestration; carbon stock; climate change mitigation; Essera district; plantation forest

1. Introduction

Forests serve as critical carbon sinks, absorbing atmospheric carbon dioxide (CO₂) and helping mitigate global climate change. Among forest ecosystems, plantation forests composed of fast-growing species such as *Eucalyptus camaldulensis* and *Cupressus lusitanica* are particularly important for their rapid carbon accumulation [1, 2].

In Ethiopia, deforestation and land degradation remain significant challenges. Plantation forestry has therefore been promoted as part of national green development policies and REDD+ initiatives, aimed at enhancing carbon sequestration and supporting rural livelihoods [3]. *E. camaldulensis* (red gum), widely planted for fuelwood and construction, is valued for its adaptability and rapid growth, while *C. lusitanica* (Mexican cypress) is preferred in highland areas for timber and shelter [4, 5]. Despite some ecological concerns, both species remain central to Ethiopia's forestry sector.

In South Western Ethiopia, including Essera District, plantation forests of these species are widespread. However, local empirical data on biomass and carbon storage remain limited. Quantifying aboveground biomass (AGB) and soil

organic carbon (SOC) provides a scientific basis for sustainable plantation management and carbon accounting.

This study aimed to estimate and compare the carbon sequestration potential of *E. camaldulensis* and *C. lusitanica* plantations in Essera District, using field measurements of diameter at breast height (DBH), tree height, and biomass equations. Findings contribute to national climate strategies and inform land-use planning.

2. Materials and Methods

2.1. Explanation of the Research Area. The study was carried out in the South West Ethiopian People's Region, specifically in Essera Woreda of the Dawro Zone, southwestern Ethiopia. Bale serves as the administrative center of the woreda, which is located within the Omo Basin. Essera is bordered by Mareka Woreda to the east, Tocha Woreda to the north, Konta Special Woreda to the west, Loma Woreda to the southeast, and the Gamo Gofa Zone to the south.

According to the 2007 Population and Housing Census, the woreda had an estimated total population of 82,218, with 41,762 males and 40,456 females. Administratively, the

district is divided into 29 kebeles. The area is characterized by rugged topography and covers a total land area of 106,021.26 ha. Geographically, it lies between 6°38'00" and 7°6'00" N latitude and 36°38'00" to 37°13'00" E longitude, with elevations ranging from 501 to 2500 m above sea level.

In terms of agroecology, the area consists of 47% tropical, 32% subtropical, and 21% temperate zones. The annual mean temperature ranges from 15.1°C to 27.5°C. The rainfall pattern is bimodal, with a short rainy season occurring between February and March and a long rainy season from May to September. The average annual rainfall ranges from 1201 to 1800 mm [6].

Land use distribution in the woreda includes 38.4% cultivated land; 13.39% grazing land; 16.81% forest, bush, and shrub land; 17.09% cultivable land; and 14.31% categorized as other land uses. The livestock population is substantial, with an estimated 313,094 cattle, 113,554 sheep, 45,703 goats, 7081 horses, 1934 mules, 5064 donkeys, 157,996 chickens, and 28,557 traditional beehives [7]. Figure 1 indicated the map of a specific study area.

2.2. Data Collection. Ten 20 × 20 m (0.04 ha) quadrats were randomly established per species ($n = 20$ total), with DBH (cm) and height (m) measured for all trees ≥ 5 cm DBH. Sampling intensity was determined based on forest homogeneity and logistical constraints, aligning with protocols used in similar studies [8].

For each quadrat, the DBH and total height of trees in quadrat were recorded.

2.3. Estimating Biomass and Carbon. AGB uncertainty was propagated using standard error ($\pm$ SE) from allometric equation parameters [9]. SOC estimates included bulk density variability (± 0.1 g/cm³) based on triplicate core samples per quadrat.

$$\text{AGB} = 0.0673\rho \times H \times D^{20.976}, \quad (1)$$

where

- AGB = aboveground biomass (kg)
- D = DBH (cm)
- H = height (m)
- ρ = wood density (g/cm³)
 - *E. camaldulensis* = 0.60
 - *C. lusitanica* = 0.45

2.4. Conversion to Carbon and CO₂

- Carbon stock (C) = $0.47 \times \text{AGB}$
- CO₂ equivalent = $C \times 3.67$

2.5. SOC. The SOC stock (tC/ha) was estimated using the following formula:

$$\text{SOC (tC/ha)} = \text{OC} \times \text{BD} \times D \times 10, \quad (2)$$

where

- OC = organic carbon (%)
- BD = bulk density (g/cm³), determined using a core sampler
- D = sampling depth in meters (0.3 m for 30 cm)
- 10 = conversion factor to express in tC/ha

Bulk density was measured by oven-drying known-volume core samples at 105°C for 24 h. SOC values were averaged across all quadrats to estimate the carbon stock per hectare.

This study focused on AGB and SOC due to resource constraints. Below-ground biomass, though critical for full carbon accounting, was not measured but should be prioritized in future work [1].

3. Results and Discussion

3.1. Results

3.1.1. Tree Growth Attributes and Age. Average DBH and height were 23.70 cm and 16.60 m for *E. camaldulensis* and 26.17 cm and 17.37 m for *C. lusitanica*. The larger values in *Cupressus* reflect its older plantation age (12 years vs. 10 years for *Eucalyptus*).

3.2. Biomass and Carbon Estimates per Plot (10 Sample Plots' Average). Biomass and carbon estimates are shown in Table 1.

3.3. Biomass and Carbon Stock per Hectare. Biomass and carbon stock per hectare is shown in Table 2.

3.4. SOC. SOC contains the following:

- ✓ Bulk density = 1.2 g/cm³
- ✓ Soil carbon = 2.0% (based on Walkley–Black reference for forested soils)
- ✓ Sampling depth = 30 cm

$$\text{SOC (t/ha)} = \text{Bulk Density (g/cm}^3\text{)} \times \text{Carbon (\%)} \times \text{Soil Depth (cm)} \times 10. \quad (3)$$

Then,

$$\text{SOC} = 1.2 \times 2.0\% \times 30 \times 10 = 72 \text{ t/ha}. \quad (4)$$

SOC was estimated at 72.00 tC/ha across both plantation types. This contribution is substantial, emphasizing the role of soils in long-term carbon sequestration.

3.5. Comparison With Biomass Carbon Pools. The comparison with biomass carbon pools is shown in Table 3.

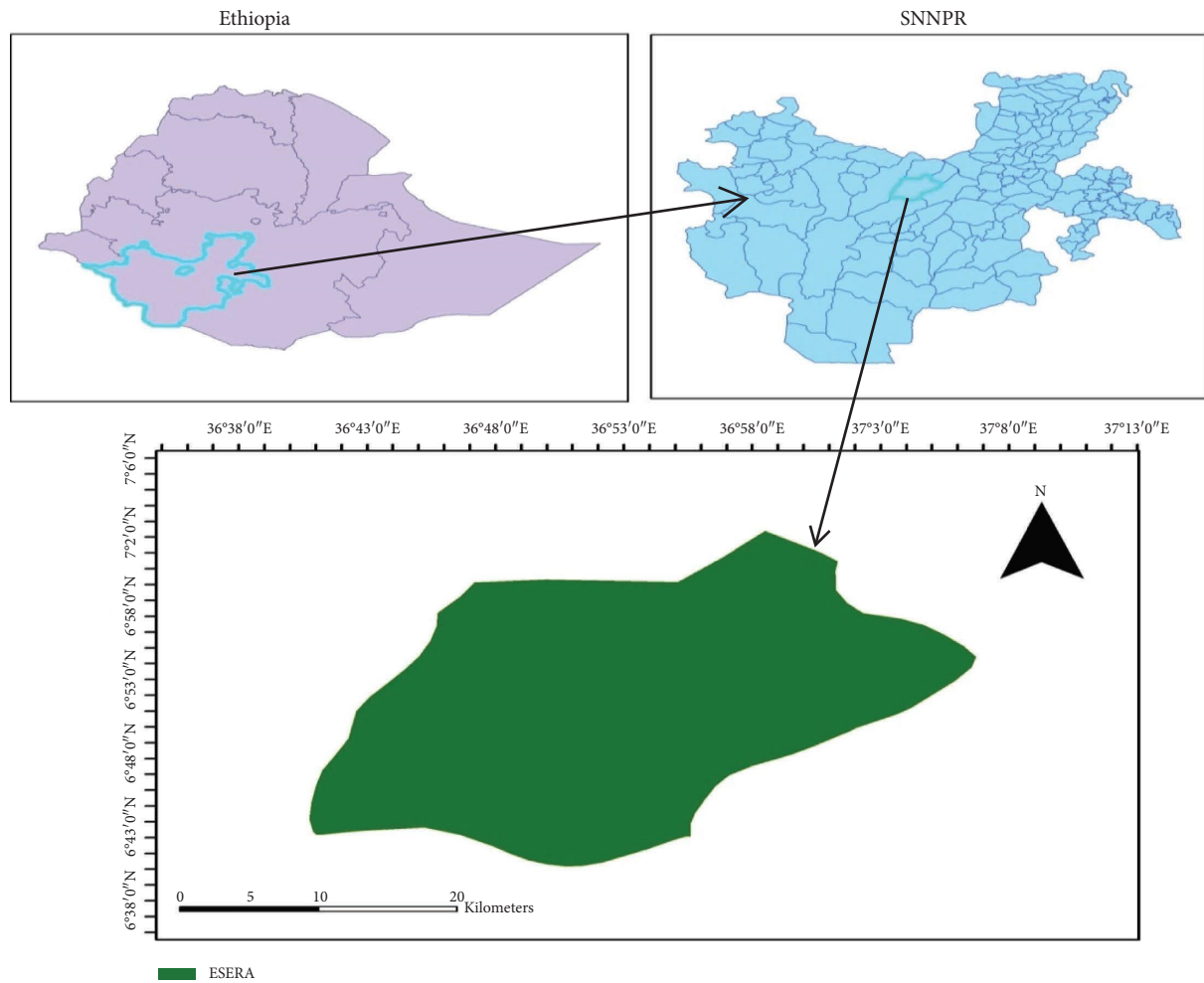


FIGURE 1: Map of Essera District.

TABLE 1: Biomass and carbon estimates.

Species	Avg AGB/tree (kg)	Total AGB (kg)	Carbon (t)	CO ₂ equivalent (t)
<i>Eucalyptus camaldulensis</i>	329.40	3294	1.55	5.68
<i>Cupressus lusitanica</i>	341.70	3417	1.61	5.91

TABLE 2: Biomass and carbon stock per hectare.

Species	Biomass (t/ha)	Carbon stock (t/ha)	CO ₂ equivalent (t/ha)
<i>Eucalyptus camaldulensis</i>	263.52	123.85	454.56
<i>Cupressus lusitanica</i>	273.36	128.48	471.53

Note: The average AGB was 329.40 kg/tree for *Eucalyptus* and 341.70 kg/tree for *Cupressus*. Converted to per-hectare values, carbon stock was 123.85 and 128.48 tC/ha, respectively.

TABLE 3: Comparison with biomass carbon pools.

Component	<i>Eucalyptus camaldulensis</i> (tC/ha)	<i>Cupressus lusitanica</i> (tC/ha)
Aboveground C stock	123.85	128.48
Soil organic carbon (SOC)	72	72
Total C stock/ha	195.85	200.48

4. Discussion

4.1. DBH and Height as Indicators of Tree Growth and Biomass. DBH and tree height are foundational parameters in forest biomass and carbon stock estimation. In this study, *C. lusitanica* recorded a mean DBH of 26.2 cm and a height of 17.4 m, slightly exceeding the corresponding values for *E. camaldulensis* (DBH = 23.7 cm, height = 16.6 m) as Table 4 indicated. This reflects the species' different growth strategies, as *Cupressus* in Table 5 tends to exhibit more persistent growth over longer periods [10], while *Eucalyptus* typically grows rapidly in early stages but stabilizes after mid-rotation age.

DBH and height are strongly correlated with biomass [11]. Numerous studies (e.g., [12]) have demonstrated that small increases in DBH significantly boost biomass accumulation, especially in mature trees. In the current study, these biometric traits laid the foundation for allometric biomass estimations, illustrating their reliability as predictors of forest carbon dynamics.

4.2. AGB Estimation and Species Contribution. The AGB results revealed substantial carbon storage potential in both species. *E. camaldulensis* had an average AGB of 329.4 kg/tree, while *C. lusitanica* reached 341.7 kg/tree. When extrapolated to the hectare scale using tree density, this equates to 123.85 and 128.48 tC/ha for *Eucalyptus* and *Cupressus*, respectively (Tables 1 and 6). Additionally, Table 2 shows that biomass and carbon stock per hectare of both tree species are *E. camaldulensis* 263.52 t/ha and *C. lusitanica* 273.36 t/hectare, and Figure 2 shows the image of *C. lusitanica* of the study area.

These values are consistent with other studies in similar ecological settings. For instance, the authors in [8] recorded plantation AGB ranging from 110 to 160 tC/ha in the Ethiopian highlands, suggesting that both species fall within expected carbon sequestration performance for exotic plantations.

These data confirm that *Cupressus*, although slower-growing initially, may outperform *Eucalyptus* over time in terms of cumulative biomass, largely due to its higher wood density and longevity [13].

4.3. SOC Storage Under Plantation Forests. In addition to tree biomass, SOC was assessed using IPCC Tier 1 default values and local soil attributes. SOC was estimated at approximately 72 tC/ha for both plantation types (Table 3). This finding is in line with the authors in [8], who found SOC between 60 and 90 tC/ha under different plantation species in southwest Ethiopia.

SOC plays a crucial role in long-term carbon storage, and its accumulation depends on factors such as litter input, root turnover, and microbial activity [14]. Both *Eucalyptus* and *Cupressus* contribute significant leaf and woody litter, enhancing SOC over time. However, there are also concerns that *Eucalyptus* plantations may lead to long-term SOC depletion under certain soil and management conditions [15], emphasizing the need for careful species-site matching.

TABLE 4: DBH, height, and biomass for all 10 quadrats (*Eucalyptus camaldulensis*).

Quadrats	DBH (cm)	Height (m)	Trees per quadrant	AGB (kg)
1	23.04	16.13	150	326
2	24.42	17.10	133	370
3	23.70	16.59	142	347
4	24.08	16.86	137	359
5	20.81	14.57	184	264
6	22.45	15.72	158	309
7	22.66	15.87	155	317
8	23.62	16.54	143	345
9	22.75	15.93	154	321
10	23.33	16.33	146	336
Average	23.7	16.6		329.4

Note: Values represent mean $\pm$ SE. *Cupressus* DBH: 26.2 ± 0.5 cm; *Eucalyptus* DBH: 23.7 ± 0.4 cm.

TABLE 5: DBH, height, and biomass for all 10 quadrats (*Cupressus lusitanica*).

Quadrats	DBH (cm)	Height (m)	Trees per quadrant	AGB (kg)
1	24.80	16.12	129	309
2	25.50	16.58	123	325
3	26.20	17.03	116	342
4	27.01	17.55	109	360
5	26.50	17.23	113	350
6	25.90	16.84	119	337
7	27.40	17.81	106	369
8	28.01	18.20	102	384
9	26.80	17.42	111	356
10	27.61	17.94	104	375
Average	26.17	17.37		341.7 kg/tree

Note: Values represent mean $\pm$ SE. *Cupressus* DBH: 26.2 ± 0.5 cm; *Eucalyptus* DBH: 23.7 ± 0.4 cm.

TABLE 6: Average DBH, height, and age of plantation forest in Essera.

Species	Avg DBH (cm)	Avg height (m)	Age (years)
<i>Eucalyptus camaldulensis</i>	23.70	16.60	10
<i>Cupressus lusitanica</i>	26.17	17.37	12

SOC (72 tC/ha) exceeded global averages for plantations [1], likely due to high litter input. However, *Eucalyptus*' allelopathic effects may reduce long-term SOC [15], necessitating species-specific soil monitoring.

4.4. DBH, Height, and Tree Age Linkage of Study Forest. The DBH and tree height are widely recognized as strong indicators of tree age and growth performance in forest plantations. In this study, the average DBH and height of *E. camaldulensis* were 23.7 cm and 16.6 m, respectively, while *C. lusitanica* exhibited slightly higher values, with an average DBH of 26.2 cm and height of 17.4 m. These metrics suggest that the plantation stands are within a typical mid-rotation stage. As record about the forest indicated, the age



FIGURE 2: *Cupressus lusitanica*.

for *Eucalyptus* 10 and 12 years for *Cupressus* that was in line with species-specific growth rates reported in Ethiopian and East African contexts ([15, 16]).

E. camaldulensis is known for its rapid early growth, often achieving DBH increments of 2.0–2.5 cm/year under favorable conditions [12]. Similarly, *C. lusitanica* demonstrates moderate but steady growth, typically reaching 25–30 cm DBH at ages 12–15 years, particularly in the Ethiopian highlands with moderate rainfall and fertile soils [18].

The observed correlation between DBH and height in both species also aligns with typical allometric patterns where height increment tends to stabilize after canopy closure, while DBH continues to increase due to radial stem expansion [9]. This suggests that *C. lusitanica*, with a slightly larger DBH and height, is older or more competitive within the stand structure.

Understanding the interplay between DBH, height, and age is crucial for biomass and carbon estimation. Since both DBH and height are primary inputs in allometric biomass equations, even modest differences in these variables lead to significant variations in estimated biomass and carbon stock. For instance, *C. lusitanica*'s higher DBH translated into greater AGB (341.7 vs. 329.4 kg/tree) and a higher per-hectare carbon stock (128.48 vs. 123.85 tC/ha) compared to *E. camaldulensis*, despite a similar tree density.

These findings are consistent with prior research in Ethiopian plantations, which demonstrated that species selection, site quality, and age significantly affect productivity and carbon sequestration capacity [8, 14]. Therefore, both *Eucalyptus* and *Cupressus* plantations in Essera District offer substantial carbon sequestration benefits, but with slight differences influenced by age and growth form.

4.5. Comparison of *Eucalyptus* Versus *Cupressus* in Carbon Accumulation. Findings align with previous studies [8, 19], confirming the importance of plantation forestry in Ethiopia's carbon balance. *Cupressus* appears to store more carbon than many lighter softwoods, owing to its moderate wood density and slower decomposition rate, while *Eucalyptus* offers rapid early growth but may impact soil fertility under poor management. These results highlight the need for species-site matching and sustainable management.

Additionally, *Cupressus* may contribute more stable litter to soil organic matter due to its slower decomposition rates, which could enhance SOC over time [10]. Conversely, *Eucalyptus* plantations are often criticized for their allelopathic effects and rapid nutrient cycling, which can potentially lower soil fertility and SOC in the long term [19].

4.6. Total Ecosystem Carbon Stock and Carbon Sequestration Potential. Combined AGB and SOC yielded total ecosystem carbon stocks of 195.85 tC/ha for *Eucalyptus* and 200.48 tC/ha for *Cupressus*. In CO₂ equivalent, these values correspond to over 700 tCO₂/ha.

These figures are substantial, especially in comparison to degraded or unstocked lands, which often store less than 50 tC/ha [1]. When converted to CO₂ equivalents (using the factor 3.67), the sequestration potential is approximately 718.78 tCO₂/ha for *Cupressus* and 718.78 tCO₂/ha for *Eucalyptus*, indicating high climate mitigation potential.

The data reinforce the role of well-managed plantations in national and global efforts to combat climate change. Both species offer tangible benefits for carbon sequestration programs, but species selection should consider broader ecological impacts and land-use goals.

Finally, these results align with Ethiopia's REDD+ targets, demonstrating that mixed-species plantations could enhance carbon stocks while mitigating risks (e.g., pest outbreaks). We recommend integrating soil carbon credits into national accounting frameworks.

5. Conclusion and Recommendation

5.1. Conclusion. This study assessed the carbon sequestration potential of two plantation species *E. camaldulensis* and *C. lusitanica* in Essera District, Dawro Zone, South Western Ethiopia. By analyzing key biophysical parameters including DBH, tree height, and estimated biomass across 10 quadrats, the study quantified both AGB and SOC stocks.

The results revealed that both species possess substantial carbon storage capacity. *C. lusitanica* showed a slightly higher average AGB (341.7 kg/tree) compared to *E. camaldulensis* (329.4 kg/tree), with corresponding carbon stocks of 128.48 and 123.85 tC/ha, respectively. SOC was estimated at approximately 72 tC/ha for both plantation types. When converted into CO₂ equivalents, total ecosystem carbon sequestration was over 700 tCO₂/ha for both species, underlining their significant role in climate change mitigation.

Additionally, the findings demonstrate strong correlations between DBH, height, and estimated tree age, highlighting the importance of age and growth dynamics in carbon accumulation. *C. lusitanica* appears to maintain higher carbon sequestration potential over longer periods, while *E. camaldulensis* offers faster early growth.

The study confirms that afforestation and reforestation using appropriate species in the region can greatly contribute to national climate strategies and international commitments such as REDD+ and the Paris Agreement. Moreover, integrating soil carbon conservation with AGB management provides a more comprehensive understanding of carbon dynamics in plantation ecosystems.

In conclusion, plantation forests in Essera District serve as vital carbon sinks. Sustainable management, species selection, and long-term monitoring are crucial for optimizing their environmental benefits and ensuring their contribution to climate resilience and ecological sustainability.

And finally, both *E. camaldulensis* and *C. lusitanica* plantations in Essera District significantly contribute to carbon sequestration. While *Cupressus* stores slightly more carbon due to higher DBH and density, *Eucalyptus* demonstrates faster growth. Together, they provide critical climate mitigation benefits.

5.2. Recommendations

- Extend rotation periods: Longer harvesting cycles can maximize carbon sequestration, especially for *Cupressus*.
- Monitor soil carbon: SOC should be integrated into plantation monitoring systems.
- Site-specific species choice: Select species according to soil fertility and ecological conditions to avoid long-term degradation.
- Support carbon accounting: Results should be integrated into national REDD+ and climate mitigation strategies.

Data Availability Statement

The data used are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

The authors received no financial support for the research authorship and/or publication of this article.

Acknowledgments

We would like to thank Wolaita Sodo University for offering different support to conduct this research to offer. We also extend our sincere thanks to Essera Woreda Natural Resource Management Office, Office of Environmental Protection and Forest staff member, and local communities for giving us an opportunity to pursue this research. We would like to thank Sciforum to publish the abstract of this paper with Submission ID: sciforum-095546 in the 4th International Electronic Conference on Forests.

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