

BIOMASS AND CARBON DYNAMICS IN DRY AFROMONTANE FOREST OF ETHIOPIA: A SYSTEMATIC REVIEW

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ABSTRACT

Dry afro-montane forests are important for climate change mitigation in Ethiopia, yet a systematic synthesis of their biomass and carbon storage capacity is lacking. This review aims to (1) quantify the biomass and carbon stocks in these forests, (2) map their geographic distribution, and (3) identify the key biophysical and anthropogenic factors driving carbon stock variation. Following the PRISMA guidelines, we systematically reviewed 72 relevant studies (2000–2025) identified from Web of Science, Scopus, PubMed, and Google Scholar. The results showed that aboveground biomass (AGB) ranged from $35.1 \pm 16.6 \text{ t ha}^{-1}$ in Desa Forest to $720.7 \pm 503 \text{ t ha}^{-1}$ in Banja Forest, with belowground biomass (BGB) following a similar pattern and generally representing 18–22 % of AGB. Soil organic carbon (0–30 cm depth) also varies substantially from $58 \pm 7.6 \text{ t ha}^{-1}$ in Gara Muktar to $277.6 \pm 11.6 \text{ t ha}^{-1}$ in Egdu Forest. Forests such as Banja, Gedo, Egdu, Ades, and Zafenigus show particularly high AGB, highlighting the capacity of well-conserved high forests to store roughly 215–425 t ha^{-1} , depending on site conditions. Factors contributing to this variation include measurement errors, the choice of allometric equations for biomass and carbon estimation, species composition and community structure, and topographic factors such as altitude and slope. Additionally, human disturbances play a significant role. Future research focuses on integrating advanced remote sensing technologies, particularly LiDAR, and applying climatic and biogeochemical models (e.g., CO₂Flux, BIOME-BGC) to simulate future biomass and carbon dynamics.

Keywords: Dry afro-montane forest, Biomass, Carbon, Climate change,

INTRODUCTION

Forests are one of the natural resources that help reduce the effects of climate change. Additionally, it prevents soil erosion, regulates water flow, and reduces the risk of floods and droughts (FAO, 2020). According to the Intergovernmental Panel on Climate Change (IPCC), forests absorb nearly one-third of the CO₂ released from burning fossil fuels each year, making them essential for maintaining the global carbon balance (IPCC, 2021).

Furthermore, it supports biodiversity, which strengthens ecosystem resilience in the face of climate change. Diverse plant and animal species contribute to healthy ecosystems that can better adapt to changing environmental conditions (Thompson, 2009). Forests worldwide are responsible for storing an estimated 1146 gigatons of carbon (GtC) (Kirschbaum, 2003). A significant portion of this carbon is contained within soils and leaf litter (44.71 %), live biomass such as trees (44.27 %), and dead wood (11.02 %) (Ravindranath & Ostwald, 2008). These mechanisms are fundamental in maintaining the delicate balance of natural ecosystems and significantly contribute to the overall stability of our planet (Malhi, 2010).

As a tropical nation with significant forest cover, Ethiopia's forest ecosystems play a crucial role in both regional and global carbon cycles. These forests are categorized into four vegetation types, such as Moist afro-montane forest, Dry afro-montane forest, Combretum Terminalia, and Acacia Commiphora (UN-REDD, 2017) and it covers about 15 % of the land mass. Dry Afro-montane Forest is the major one found in Ethiopia's northern, northwestern, central, southern, southeastern, and southwestern regions at elevations ranging from 1800 to 3400 meters above sea level (Demissew & Friis, 2009; Friis & Demissew, 2011). The major species of this vegetation type are *Juniperus procera*, *Podocarpus falcatus*, *Prunus africana*, *Ekebergia capensis*, *Olea spp.*, *Apodyttes dimidiata*, *Allophylus abyssinica*, *Euphorbia ampliphylla*, *Olinia rochetiana*, *Myrsine melanophloeos*, *Dovyalis abyssinica*, *Myrsine africana*, and *Calpurnia aurea*.

The biome has an indispensable role for various climate and restoration initiatives at both international and national levels, including REDD+, the Climate-Resilient Green Economy (CRGE) strategy, and Forest Landscape Restoration (FRL). As part of the REDD+ initiative, the country has pledged to sequester 10.2 million t CO₂ annually through the forest reference level for afforestation, aligning with results-based payment mechanisms (UN-REDD, 2017). Additionally, with FRL, a country aims to restore 22 million hectares of degraded land by 2030 (Pistorius *et al.*, 2017). Within this framework, the dry afro-montane forest is particularly significant. The biome has an annual forest gain of 12,785 ha, surpassing other biomes during the period from 2000 to 2013 (UN-REDD, 2017). Moreover, the implementation of Participatory Forest Management (PFM) in this biome is crucial for the success of REDD+ in establishing robust grassroots institutions that can effectively tackle deforestation and degradation issues (Lemenih *et al.*, 2015; Siraj *et al.*, 2018). These initiatives require the presentation of information about the past and current rate of forest degradation, deforestation, forest conservation, and forest carbon enhancement activity. Moreover, these types of information need a science-based assessment and accurate quantification (Henry *et al.*, 2011). Additionally, understanding the factors that affect biomass stock forest ecosystems is essential for effective forest management strategies aimed at mitigating climate change (Tetemke *et al.*, 2021).

This review synthesizes current knowledge on biomass and carbon pools in dry afro-montane forest, drivers of carbon variation across the sites, and the implications for climate change mitigation policy in Ethiopia. So, the primary aim of this review was to compile evidence on how dry afro-montane forests contribute to climate change regulation through the accumulation of biomass and carbon, while also evaluating related factors. Additionally, geolocating the existing dry afro-montane forest of Ethiopia. It involved gathering and presenting scientific data on the role of various biomass and carbon pools, such as above-ground and below-ground biomass and soil carbon, in mitigating climate change. Additionally, the paper offers valuable scientific insights to researchers, government bodies, and policymakers regarding management interventions and understanding the factors influencing biomass stock in forest ecosystems.

MATERIAL AND METHOD.

Study design and literature search

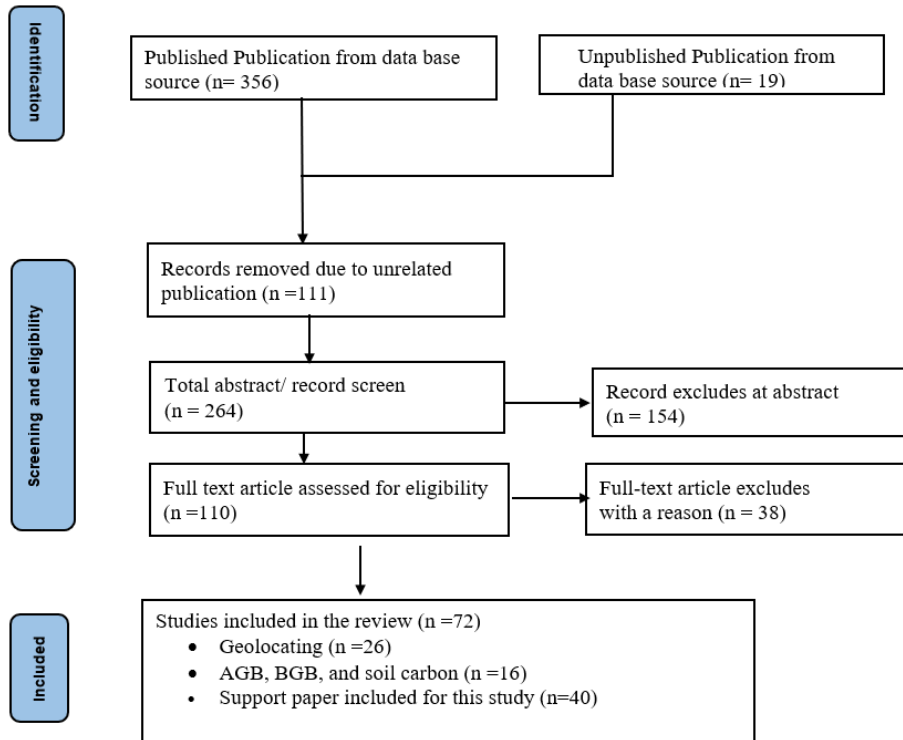
This review employed a systematic approach to gather, analyze, and synthesize existing literature on how dry afromontane forests contribute to climate change regulation through the accumulation of biomass and carbon, and factors associated with it. Data were collected and compiled from the review of peer-reviewed papers, book chapters, conference papers, as well as PhD dissertations and MSc theses available on the internet. The search was conducted using Web of Science, Scopus, PubMed, and Google Scholar with keywords such as “above ground biomass”, “below ground biomass”, “above ground carbon”, “below ground carbon”, “soil carbon” “Ethiopia”, “carbon dynamics”, “biomass Dynamics”, and “dry afromontane forest” were used to identify relevant articles, reports, and grey literature published from 2000 to 2025.

Literature inclusion and exclusion criteria

This systematic review paper examines scientific published and unpublished papers about biomass and carbon dynamics in the dry afromontane forest of Ethiopia. Based on the following criteria, the inclusion and exclusion of scientific paper was undertaken: (i) Peer-reviewed articles and grey literature focusing on forest biomass and soil, and the factors associated with dry afromontane forest; (ii) Studies conducted in the dry afromontane forests of Ethiopia. However, some studies from other parts of the world were included, for the comparison and to supported ideas and relevant evidence linked to the content in Ethiopia; (iii) studies that provided either quantitative or qualitative data on addressing the factor affecting the biomass and carbon variation in dry afromontane forest; (iv) Research that related with examining the contribution soil carbon with in dry afromontane and associated factors; (v) Studies that clearly describe data sources, sampling design, measurements, and analytical methods; (vi) Studies undertaken within the 2000–2025; and (vii) only studies published in English were eligible for inclusion.

Identification and screening of the studies

A diagram was used to illustrate the screen of articles used for this review (Fig. 1). Following the search in Google, Web of Science, Scopus, PubMed, and Google Scholar, 356 published and 19 unpublished articles were used for this review. During the screening and eligibility phase, 111 publications and records were removed due to unrelated publications. Additionally, after title/abstract screening, 154 records were excluded, and 38 records were removed after full text reading. Subsequently, a full-text evaluation was performed on the remaining 72 publications, which were incorporated into the review.

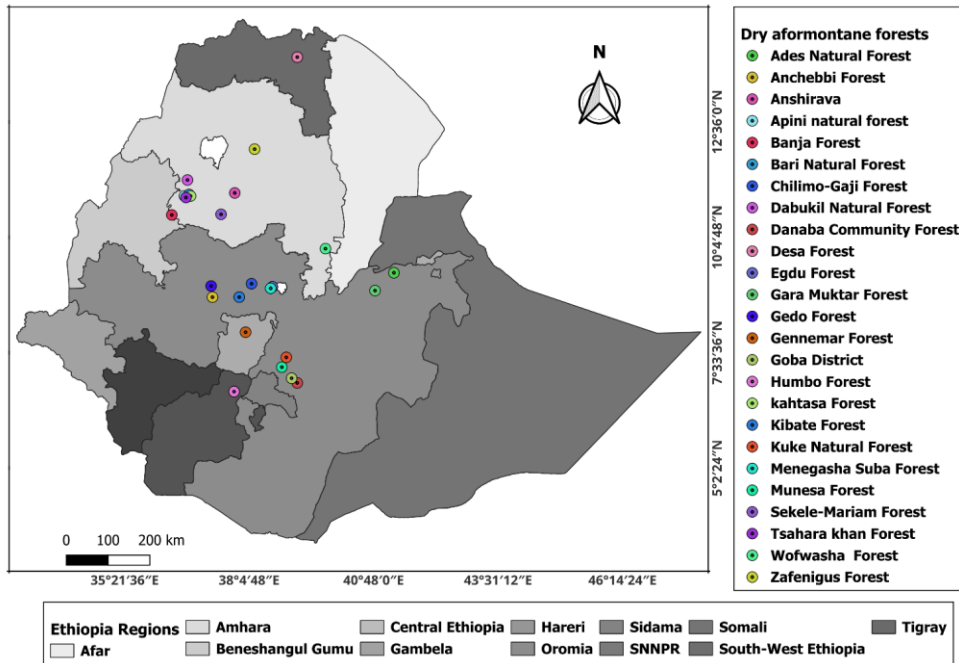
Fig. 1: Flow diagram illustrating the process of conducting literature searches and screening articles

RESULT AND DISCUSSION

Geographical distribution of dry afro-montane forest in Ethiopia.

The map illustrates the geographical distribution of the existing dry Afro-montane forest (Fig. 2). The majority of these forests are located in the Oromia and Amhara regions, comprising 12 and 11 sites, respectively. This is followed by the Central Ethiopia region, Tigray, and the Southern Nations, Nationalities, and Peoples' Region (SNNPR), each represented by one site. The existence of Dry Afro-montane Forest is more concentrated in the northern, northeastern, northwestern, central, southern, and southeastern highlands of Ethiopia. This is due to favorable Altitude, topography, and climate conditions. According to Demissew & Friis (2009) and Friis (2011), the dry afro-montane forest is located at elevations of 1800 to 3400 m, with annual precipitation ranging from 400 to 1500 mm and an average annual temperature of 14-25 °C. The major soil reference group commonly found in Ethiopian highlands and dry afro-montane forest is Nitisols, which are deep, well-drained red clay soils with strong structure and high porosity, and Vertisols, clay-rich soils formed on fine-textured volcanic or limestone-derived parent materials (Ali *et al.*, 2024). Followed by Cambisols, Leptosols, and Luvisols, together cover most of the surface.

Fig. 2: Geographical distribution of dry afromontane forests in Ethiopia



The biomass contribution of the dry afromontane forest

Compiles results from 18 dry Afromontane forest sites across Ethiopia, drawn from studies published between 2011 and 2025 (Table 1). Each study reports estimates of above-ground biomass (AGB), below-ground biomass (BGB), above-ground carbon (AGC), and Below-ground carbon (BGC), in many cases, soil-carbon stocks. Of all studies, five reported results as aboveground biomass (AGB) and belowground biomass (BGB), eight reported aboveground and belowground carbon, and the remaining three presented results for both biomass and carbon. For the comparison, we used the default value of 0.47 to convert both above- and belowground carbon into above- and belowground biomass, assuming that biomass is 47 % carbon (Chave *et al.*, 2005; Eggleston *et al.*, 2006; Kumar & Sharma, 2014).

Across the dataset, AGB shows a very wide range from $35.1 \pm 16.6 \text{ t ha}^{-1}$ in Desa Forest, to over $720.7 \pm 503 \text{ t ha}^{-1}$ in Banja Forest. The results indicate that AGB varied significantly among sites and within sites. For example, in Banja Forest, the mean AGB was 720 t ha^{-1} , while the minimum and maximum AGB values in the sampled plots were 12.61 and $1187.04 \text{ t ha}^{-1}$, respectively. Such variability illustrates how forest structure, management, and environmental conditions control the capacity of these ecosystems to accumulate and store carbon. The comparison of national AGB for the dry afromontane forest of Ethiopia (Fig. 3) showed that most of the studies had higher AGB than the national average, which is 113 t ha^{-1} (UN-REDD, 2017). Moreover, a comparative study was undertaken involving Kenya's dry zone tropical forests, which have an AGB of 128.3 t ha^{-1} (Namaswa *et al.*, 2025), Tanzania's tropical rainforests, with an AGB of 177.0 t ha^{-1} (Mauya & Madundo, 2021), and Cameroon's tropical rainforests, which are estimated to have an AGB of $318.04 \text{ tons ha}^{-1}$ (Zapfack *et al.*, 2016). The comparison shows that, among the 16 sites, six dry afromontane forest sites exhibit higher mean AGB than Cameroon's tropical rainforests. In addition, eight

and thirteen sites have higher mean AGB than those reported for Tanzania's tropical rainforests and Kenya's dry-zone tropical forests, respectively. Four forest sites exhibited AGB values below the Ethiopian national average for dry afro-montane forest. Forests including Banja, Gedo, Egdu, Ades, and Zafenigus demonstrate substantially higher AGB than other dry Afro-montane forests evaluated in this review. This underscores the significant biomass-storage capacity of well-conserved natural high forests, which, depending on site-specific conditions, can store approximately 215–425 t ha⁻¹. (Moges *et al.*, 2010; Tsegaye, 2010).

Table 1: Summary of reported mean and standard deviation AGB and BGB values from the reviewed literature of the dry afro-montane forest of Ethiopia

Authors	Site	AGB (t/ha)	BGB (t/ha)	Soil carbon (t/ha)
Abere et al., 2017	Banja Forest	720.7± 503	144.1± 100.6	230.8 ± 68.9
Meragiaw et al., 2021	kibate Forest	76.6±8.6	15.3±1.82	N/A
Gebeyehu et al., 2019	Tsahare Kan Forest	170.1±31.9	34±6.4	100.6±4.5
Gebeyehu et al., 2019	Apini Forest	171.2±51.3	34.2±10.3	175.1±21.1
Gebeyehu et al., 2019	Dabkuli Forest	207.4±47.2	41.5±9.4	138.2±10.6
Gebeyehu et al., 2019	Bari Forest	269.1±46.8	53.8±9.4	164.3±15.5
Gebeyehu et al., 2019	Kahatsa Forest	140.8±37.1	27.7±7.4	168.4±10.9
Gelaw et al., 2025	Ziba Forest	N/A	N/A	100 ± 20.7
Gelaw et al., 2025	Anshirava Forest	N/A	N/A	111.4 ± 19.6
Lechisa Mosisa, 2020	Anchebbi Forest	234.9±25.5	61.1±6.6	N/A
Aschalew, 2019	Goba District	223.4±61.7	57.4±16.9	N/A
Abera and Tesema, 2021	Zafenigus Forest	399.4±19.4	79.8±3.8	N/A
Reshad Haj et al., 2019	Ades Forest	674.5±159.6	183.4±72.3	N/A
Yohannes et al., 2015	Gedo Forest	597.9±54.7	119.6±10	N/A
Feyissa et al., 2014	Egdu Forest	591±54.7	118.3±10.9	277.6±11.6
Solomon et al., 2024	Desa Forest	35.1±16.6	9.1±4.2	71.4 ± 17.7
Woldie et al., 2025	Gara Muktar	217.2±66.4	91.3±23.2	58±7.6
Sahle, 2011	Menegasha suba	282.9±210.6	57.23 ± 40.4	121.3 ± 21

N/A: not available.

Soil carbon contribution in dry Afro-montane Forest

Soil carbon was studied in 12 of the 26 dry Afro-montane forests (Fig. 4). Egdu Forest had the highest soil carbon (277.6 ± 11.6 t ha⁻¹), followed by Banja (230.8 ± 68.9 t ha⁻¹), while Gara Muktar and Desa had the lowest (58 ± 7.6 and 71.4 ± 17.7 t ha⁻¹, respectively). In a comparative analysis of mean soil carbon in Ethiopian forests, reported as 104.032 t ha⁻¹ (Kassaye *et al.*, 2025), four forest sites exhibited lower values, whereas eight sites showed higher soil carbon values.

Fig. 3: Comparison of aboveground biomass (AGB) among different dry afromontane forest relative to the national mean for dry afromontane Forest

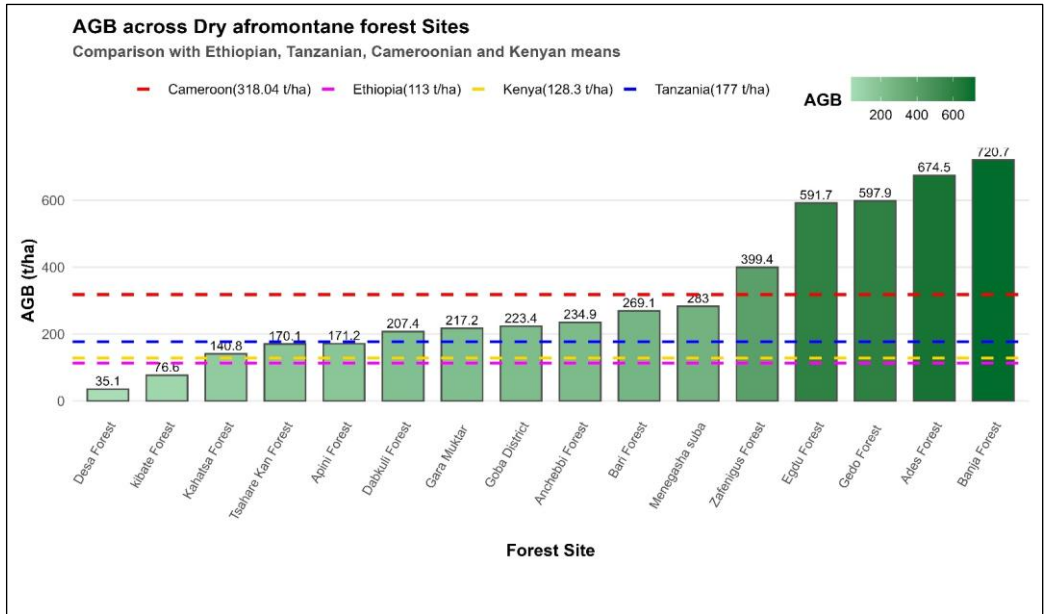
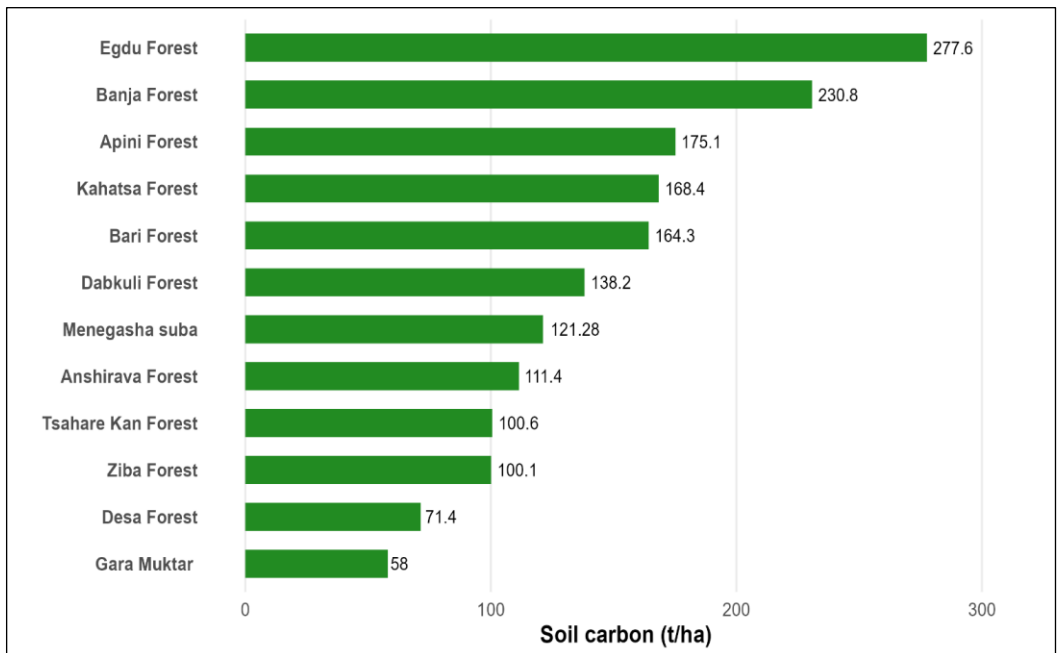


Fig. 4: Comparison of soil carbon stocks in selected dry Afromontane forests of Ethiopia (0-30 cm soil depth)



Factors affecting biomass and carbon variation in dry afro montane forest.

Forest biomass and carbon stocks in dry Afromontane forests vary widely due to the combined effects of environmental, biological, and human factors, as well as estimation errors (Fig. 5). Studies indicate that factors such as vegetation composition, structural attributes, topographic (elevation, slope, and aspect), climatic conditions, disturbances, and stand age contribute to the biomass variation (Gogoi *et al.*, 2022; Islam *et al.*, 2017; Pregitzer & Euskirchen, 2004).

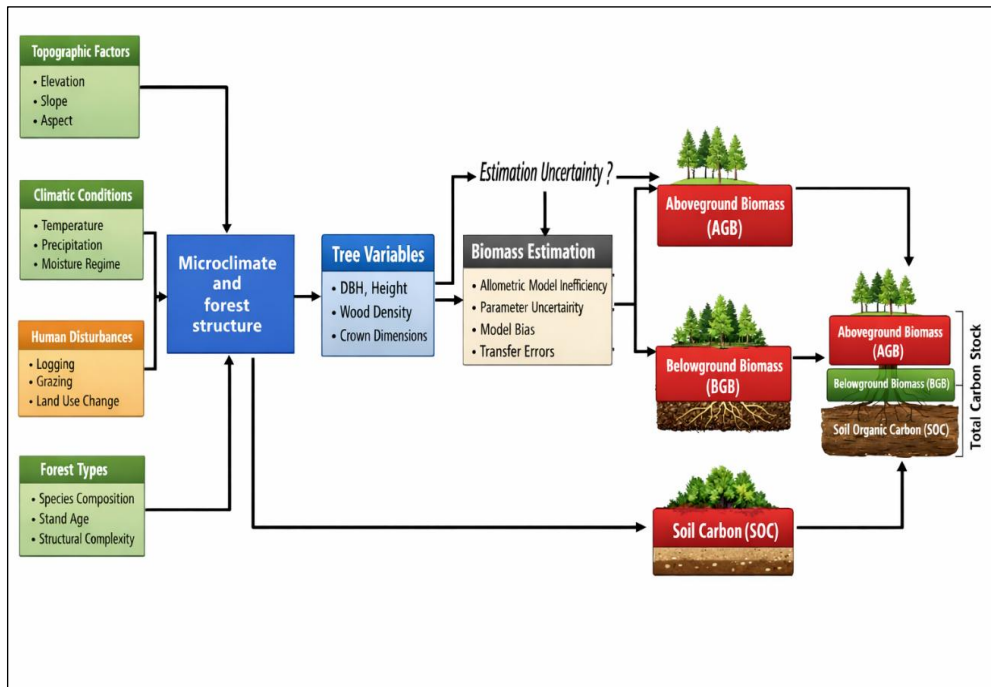
In addition, forest types, measurement error, uncertainty related to allometric models, and anthropogenic disturbance played a significant role in the variation in biomass and carbon across sites (Lasco *et al.*, 2000). The selection of allometric leads to uncertainty and error in the estimation of biomass (Basuki *et al.*, 2009; Fayolle *et al.*, 2013; Guendehou & Lehtonen, 2014). So, the Allometric equation used for the estimation of AGB in these studies was assessed. Accordingly, in the study in Egdu Forest, used (Brown *et al.*, 1989), and in Desa Forest, the estimation was undertaken by (Tetemke *et al.*, 2019), and the remaining biomass estimation was undertaken by (Chave *et al.*, 2014, 2005). The use of allometric equations like Chave *et al.* (2014 and 2005) will reduce the uncertainty in biomass estimation carried out in tropical countries like Ethiopia (Egeta *et al.*, 2023). Moreover, using local developed Allometric equation, like Tetemke *et al.* (2019) in Desa Forest, will have more importance in the estimation of biomass because it can provide accurate and reliable estimates of forest biomass and carbon stock. Since it can capture differences in tree nature and site condition (Henry *et al.*, 2011). Hence, the selection of an allometric equation will have its own impact on the variation of biomass and carbon across different sites. Additionally, measurement error also plays a role in estimating forest biomass and carbon. Since forest biomass and carbon stocks are predominantly based on plot-based field measurements of stem diameter and, occasionally, stem height. Consequently, these measurements are subject to error (Holdaway *et al.*, 2014). Various factors contribute to measurement errors, including tree form and forest structure, field methodology, the skill of the measurer, and the field conditions under which the data were collected (Butt *et al.*, 2013; Keller *et al.*, 2001). The estimation of aboveground biomass for individual trees carries an average uncertainty of 47 % of the calculated value. This uncertainty primarily stems from a 31-30 % variation linked to the allometric model, while measurement errors contribute an additional 16 % (Chave *et al.*, 2005; Djomo *et al.*, 2011).

Another important factor in biomass and carbon variation in this forest site is species composition and structure. It had a significant impact on biomass carbon density (Hu *et al.*, 2015). Forests dominated by large, high wood-density species such as *Juniperus procera*, *Olea spp*, and *Podocarpus falcatus* store more carbon than those dominated by smaller or fast-growing species. Differences in species composition also influence litter input and soil carbon (Reshad, 2019). Species composition and community structure had significant impacts on biomass carbon density

Several studies in Ethiopia have reported significant effects of altitude and slope on carbon pools. Altitudinal variation influences carbon stock in different forest components by shaping climatic conditions and soil water availability along elevation gradients. Consequently, higher aboveground carbon stocks are typically found at mid-altitudes, while lower and upper zones show moderate to low values (Gedefaw *et al.*, 2014; Kassahun *et al.*, 2015; Solomon *et al.*, 2024). In Anshirava and Ziba forests, most carbon pools increased with altitude, though in Ziba forest, higher aboveground and belowground carbon were observed at lower elevations (Asrat *et al.*, 2022). As altitude increases, both biomass and carbon content decrease in comparison to lower altitudes (Abera *et al.*, 2017; Chimdessa, 2023; Lechisa Mosisa, 2020; Lozano-García *et al.*, 2016). Since the lower altitude creates favorable

climate condition the growth of tree species (Hemp, 2006). This pattern reflects the scarcity of dense, tall trees at both ends of the forest and favorable growth conditions in the mid-altitude range (Tefaye *et al.*, 2019). However, studies suggest there is a positive relationship between altitude and forest biomass (Ahmed & Lemessa, 2024; Culmsee *et al.*, 2010; Girma *et al.*, 2014). The revision showed that dry afromontane forest is distributed 1800–3000 m above sea level, which contributes significantly to the variation in biomass and carbon across these sites. Slope is another important topographic variable affecting biomass and carbon storage. Studies indicate a positive association between slope and carbon stocks, as steep areas are less accessible and therefore subject to reduced grazing and illegal harvesting (Gebeyehu *et al.*, 2019; Kassahun *et al.*, 2015; Tefaye *et al.*, 2019). However, other studies found a decreasing trend with increasing slope, attributed to soil erosion and nutrient loss (Asrat *et al.*, 2022; Gubena & Soromessa, 2016; Simegn & Soromessa, 2015).

Fig. 5: Conceptual framework illustrating the interactions among topography, climate, human disturbances, and forest types and AGB, BGB, soil organic carbon (SOC), and total ecosystem carbon stocks



Apart from altitude variation, disturbance across the forest site will play a vital role in the variation of biomass and carbon in this forest. Since disturbance causes a reduction in the biomass accumulation and carbon sequestration potential of the forests (Bazezew *et al.*, 2015). Human disturbances such as logging, fuel wood collection, grazing, and agricultural expansion reduce biomass and alter carbon dynamics. Disturbed forests show much lower total biomass carbon stocks compared to protected sites, though restoration measures like exclosures and community forest management enhance recovery over time (Asrat *et al.*, 2022). Effective management practices such as enrichment planting, assisted natural

regeneration, and controlled grazing enhance biomass recovery and carbon sequestration (Moges *et al.*, 2010; Reshad, 2019).

Policy influences on forest biomass and carbon stock estimation

Quantification of forest biomass and carbon stocks is essential for monitoring climate change mitigation, yet several policy-related factors, particularly in developing countries, hinder accurate assessment. A key factor affecting the accuracy of estimation is weak forest governance and inconsistent land-use policies (Birhan *et al.*, 2021). The absence of stringent regulation or effective enforcement in forest management policies leads to illegal deforestation, forest degradation, and agricultural expansion, which contribute to the uncertainty in forest carbon reporting (Rahman & Miah, 2017). Additionally, inadequate institutional arrangements and financing have their own impact on the accuracy and quantification of forest biomass and carbon. Many countries, especially in the tropics, have historically lacked the capacity to implement comprehensive forest carbon monitoring systems (Austin *et al.*, 2012). However, the implementation of Monitoring, Reporting, and Verification (MRV) systems and REDD+ initiatives has an important role in filling the financial and technical gaps in forest carbon monitoring systems. For example, in Ethiopia, collaboration among universities has contributed to the development of an MRV curriculum and strengthened capacity building for monitoring and reporting forest biomass and carbon. (Bekele *et al.*, 2010).

The lack of nationally specific data and allometric equations leads to over-reliance on generalized, imported, or outdated equations, creating bias and error. In Ethiopia, the national Forest Reference Level (FRL) was developed using the pantropical model of Chave *et al.*, (2014), without species-specific, biome-based, or nationally calibrated equations. According to many studies conducted in Ethiopia, the pantropical model can increase uncertainty in forest biomass and carbon estimation. (Abich *et al.*, 2018; Tesfaye *et al.*, 2016). Another important factor is the selection of forest carbon pools; policies and inventories often focus only on aboveground biomass (trees), while neglecting other critical pools because of complexity, labor demands, time constraints, and high measurement costs, particularly for belowground biomass and soil organic carbon (SOC) (Lehtonen *et al.*, 2020).

CONCLUSION AND RECOMMENDATIONS

The review is evident that dry afro-montane forest contributes significantly to climate change mitigation through biomass and carbon accumulation. As we compared with the national average AGB for dry afro-montane forest, the amount of biomass stored in this forest type varied across sites. The review showed that different factors contributed to this variation, including measurement error and the allometric equation used in the estimation of biomass and carbon; species composition and community structure had significant impacts on biomass carbon density. Additionally, altitudinal variation plays a significant role in the variation of biomass in this forest type because the dry afro-montane forest is distributed in an altitude range from 1800 to 3400m. Moreover, Human disturbances such as logging, fuelwood collection, grazing, and agricultural expansion reduce biomass and alter carbon dynamics, and depending on the level of disturbance, the amount of carbon and biomass stored in this forest will vary.

This revision provides evidence that dry afro-montane forests have a significant role in climate change mitigation through biomass and carbon accumulation. Future research should focus on integrating advanced remote sensing technologies, particularly LiDAR; developing

species- and site-specific allometric equations for dominant trees; and applying climatic and biogeochemical models (e.g., CO₂Flux, BIOME-BGC) to simulate future biomass and carbon dynamics.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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