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ORIGINAL ARTICLE

Estimation of biomass and carbon sequestration capacity of the Surra mountain plantation forest in Gamo Highlands, Southern Ethiopia

Genesha Mada[1] | Agena Anjulo[2] | Abren Gelaw[3]

[1]Department of Geography & Environmental Studies, Arba-Minch University, Arba-Minch, Ethiopia
[2]Ethiopian Environment and Forest Research Institute, Addis Ababa, Ethiopia
[3]Environment & Natural Resource Management, Department of Geography & Environmental Studies in Arba-Minch University, Arba-Minch, Ethiopia

Correspondence
Genesha Mada, Department of Geography & Environmental Studies, Arba-Minch University, Arba-Minch, Gamo Zone, Ethiopia.
Email: geneshamada2012@gmail.com

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Abstract
This study was aimed at estimating the carbon sequestration potential of the Surra planted forest on Gughe massive of the Gamo highlands in Southern Ethiopia based on tree species type. The plantation was established on degrading pasture land in the mid-1980s during the golden era of plantation forest expansion history in Ethiopia. The Surra plantation forest was stratified upon three tree species namely E. globulus, C. lusitanica, and P. radiata. The data were collected from 32 sample plots (20 E. globulus, 10 C.lusitanica, and 2 P. radiata plots, each having 10 m*10 m in size), and were laid at random at the inner part of the plantation. The Species-specific allometric equations and the pan-tropical allometric model were used to estimate the aboveground biomass and carbon stock of the forest. The average "tree height," "diameter at breast height," and "tree stand density" per hectare were the highest for C. lusitanica and the lowest for E. globulus (except the wood density). The wood-specific density/g/cm^3 was the largest for E. globulus. The average carbon sequestered in C. lusitanica (53.9 ton/ha) was significantly larger than E. globulus (35.6 ton/ha) and P. radiata (43.8 ton/ha). The estimated average carbon stock/ha of eucalyptus was the lowest due to its low stand density caused by illegal encroachment for construction, energy, and cash income purposes. The total dry biomass and carbon sequestrated are determined by area proportion; hence, eucalyptus covered an extensive area accounting for slightly less than two-thirds of the total Surra plantation forest followed by Cupressus. The mean carbon stock (40.3 ton/ha) of the Surra plantation is lower compared with many plantation forest stock values under better management. The findings revealed that the significant variation in carbon stock with other forests despite the similarities in age, climate, location, and aspect was the result of encroachment, illegal cutting, frequent grazing, and limited protection, and call for policy attention from the Ethiopian government.

KEYWORDS
carbon sequestration, plantation-forest, Gamo highlands, etc, dry matter, wet biomass

1 | INTRODUCTION

Increasing carbon dioxide (CO_2) in the atmosphere has been aggravating global warming, variability, and change of climate worldwide (FAO, 2000). The increase in CO_2 in the atmosphere has emanated largely from anthropogenic activities such as deforestation, burning of fossil fuels, and urban and industrial expansion (Justine et al., 2015). Because of these and other reasons, the world has experienced increasing greenhouse gas emissions to the atmosphere, rising temperature, and escalating variability and change of climate since industrialization (IPCC, 2013; IPCC, 2014; Zarin et al., 2016). However, one of the recommended remedies to halt such increasing in atmospheric carbon dioxide is mitigation (carbon sequestration) through the planting of trees and maximizing of management for the existing forests (IPCC, 2006).

The concept of "carbon sequestration" is the gradual storage of carbon in biotic and abiotic (e.g., minerals, rocks, soils, and oceans) substances (Friedlingstein et al., 2021; Justine et al., 2015); it is the capture and storage of atmospheric carbon to the tissues of plants or other substances; or partly a photosynthesis-based conversion of atmospheric CO_2 to organic compounds (FAO, 2000). The carbon sequestration occurs through natural and anthropogenic processes. For instance, carbon is naturally transferred from the atmosphere to biotic carbon through the photosynthesis process so that it is stored in the form of aboveground and belowground biomass of natural forests, plantation forests, and other vegetation ecosystems (Besar et al., 2020; Bluffstone et al., 2017). "*The plantation forests*" refer to manmade forests composed of trees largely planted by the participation of the public, individuals, institutions, etc., for timber products, fuelwood, erosion prevention, flood control, CO_2 emission reduction, climate change regulation, and/or other purposes (Besar et al., 2020; IPCC, 2013; Zarin et al., 2016). The plantation forests could be developed through afforestation, reforestation, agroforestry practices, and area enclosure (Bluffstone et al., 2017). A decade ago, over 7% (264 million ha) of the global forest area was accounted for by the plantation forests (FAO, 2010).

The natural and plantation forests are valuable in sequestering carbon emitted by anthropogenic activities and in the regulation of the surface temperature and climate. This is so because the forest ecosystems retained the greatest share (80%) of the total aboveground (terrestrial) carbon stock than any other ecosystems; over 650 Gigaton (Gt) of carbon is stored by the live trees of the global forest (FAO, 2010; Justine et al., 2015). For example, about 80% of the increment in carbon storage in China was contributed by the plantation forests (Fang et al., 2007), and as well as 61.52 million tons of carbon was stored in the plantation forest in Ethiopia (WBISPP, 2004; FSR, 2018).

The carbon sequestration of forests, in addition to the climatic and environmental benefits, are providing the economic benefit in the form of a carbon fund. The carbon funds (incentives) are paid to developing countries in order to capacitate either the reduction of greenhouse gas emission rates through intensive management or via the afforestation-reforestation process (IPCC, 2013). This payment is based on the amount of carbon sequestrated, and the sequestrated amount should be assured through the scientific investigation (IPCC, 2006). And therefore, several studies have been conducted to account for the carbon stock capacity of natural forests, plantation forests, and agroforestry and also have investigated carbon losses due to deforestation and other land uses (Besar et al., 2020; Bluffstone et al., 2017; Fang et al., 2007; IPCC, 2014; Justine et al., 2015).

The biomass and carbon storage capacity of forests were quantified and evaluated based on differences in age, location, aspects, agro-climate, tree species, and causes of existence (natural or manmade) (Besar et al., 2020; Justine et al., 2015). This was because its results enable to understanding of biomass and carbon stock capacities of different tree species and help to develop appropriate forest policy and management options for the forest resource development, and to maximize the carbon mitigation capacities. Due to these, there have been different carbon retention models and approaches developed and have been implemented to get robust and standardized models that maximize accuracy (Picard et al., 2012). Since then, species-specific allometric models are better at accounting for carbon storage potentials of forests than other models (Chave et al., 2014).

Although Ethiopia has patches of natural and plantation forests in different areas, the tradition of assessing the carbon stock capacity of specific forests is a relatively recent agendum. Even if it is a recent issue, nationally estimated carbon density findings are varying among themselves, and maybe due to the application of the different methodologies, regional variability of soils, differences in topography, disparity in climate, and water holding capacity (availability) of soils as well as the forest types, and uncertainties associated with accounting method used (Yitebitu et al., 2010; FSR, 2018; Narita et al., 2018). Despite its limitation in similarities, the research on biomass and carbon stock capacity of forests in different parts of Ethiopia has been conducted. For instance, carbon finance (Yitebitu et al., 2010), carbon stock of Church forests (Tulu, 2011), aboveground biomass and carbon stock through remote sensing and allometric equation (Wondrade et al., 2015), carbon stock of woody plants (Marshet & Teshome, 2015), carbon stock of plantation tree species (Yirdaw, 2018), biomass and soil carbon stocks (Solomon et al., 2019), and aboveground biomass of introduced trees (Tesfaye et al., 2020) are among the main carbon sequestration-related studies in Ethiopia. None of these studies was confined to the areas in and around the upper Hare-Baso rivers catchment on the Gamo highlands (southern Ethiopia) while this study was conducting.

The assessment of this study was limited to the aboveground biomass despite its corresponding belowground biomass was indirectly surveyed. To account for AGB, the accuracy of determining attributes namely the H (height), DBH (diameter at breast height), and WD (wood biomass density) were inferred using species-specific equations and pan-tropical allometric models (Chave et al., 2014; Tesfaye, 2017). Its corresponding carbon stock potential was calculated by considering "The half of DM (dry matter) of the biomass is carbon" (IPCC, 2006). The main aim of this study was to estimate tree species-based biomass and carbon stock capacity of the Surra plantation forest of a single plot. The specific aims were to: quantify the biomass of the forest based on tree species, account for the carbon sequestration capacity of forest based on tree species, and compare the biomass and carbon stock capacities among the different tree species notably the eucalyptus, Cupressus, and radiata.

2 | STUDY AREA AND METHODS

2.1 | The study area descriptions

Altitudinally, the upper Hare-Baso rivers catchment is located between 2,329 and 3,442masl; astronomically is between $6^0 15'0''$ N to $6^0 22'0''$ N and $37^0 28'0''$ E to $37^0 38'0''$ E (Figure 1); and relatively is under Qogota and Chencha zuria woreda (*woreda*: is the second smallest administrative level in Ethiopia) of Gamo zone in Southern Ethiopia. The topography of the area is a part of rugged terrain of the Gamo highlands that extended north to south with rising elevations up to 4200masl (Mt. Gughe), the highest peak in the southwestern physiographic features of Ethiopia (Hurni, 1998). Predominantly, the upper Hare-Baso rivers catchment comprises two mountain peaks namely Maylo and Surra, which are seen above the surrounded lands. The mountain Maylo is the watershed divide of Hare-Deme while the mountain Surra is the watershed divide of the Baso-Hare and Baso-Deme.

According to updated Koppen's major climate classification system (Kotter et al., 2006), the agro-climate of the study area is the tropical highland climate (mountain climate type), and represented by "H" and locally named as *dega (*Hurni, 1998). 'The altitudinal interval of upper Hare-Baso rivers catchment is between 2647 and 3442masl, and the climate is locally called *dega* to *wurch* (Hurni, 1998). The mean annual rainfall of the area varies from 1100 to 1300 mm, and receives bimodal rainfall. The first rainfall season is from March to April while the second is from June to August (Abera, 2006). The average minimum and maximum temperature of the area is 18^{o}c and $23°_{C,}$ respectively (Engidawork & Bork, 2017; Mohammed, 2017; Teshome, 2015).

According to FAO-Unesco classification, the soils of the upper Hare-Baso rivers catchment is allotted under the *region 20,* and that is part of the moistest southwestern highlands of Ethiopia. The soils of the *region 20* are a part of the relief type, and t are dominated by the basaltic parent rock (FAO-Unesco, 1997). The basaltic parent rock soils of *red* and fairly deep dominant *Eutric-nitosol* are associated with *Humic-cambisols*, *Vertisols*, *Ferralsols,* and *Acrisols* (FAO-dsmw, 2017). The types of soil classification of the Surra mountain, the Surra plantation forest confined, are *orthic-acrosol, dystric-fluvisols,* and *dystris-nitisols* (FAO-dsmw, 2017)*,* and the corresponding area coverage computed via ArcGIS version 10.5 using soil map of FAO-*dsmw* are 150.3 ha, 44.6 ha, and 40 ha, respectively.

The old and historic settlement of people in the catchment depleted natural forests (Teshome, 2016). The natural forests, except in sacred places, have dwindled due to population pressure causing increment in the demand for arable land, fuelwood, and house construction materials. Although the natural forests on private lands are almost depleted, one can see here and there the patches of forests on the graveyards, meeting places (*Dubusha*), and other sacred sites (Dessalegn & Healey, 2015). The hilltops in the catchment area are covered by Afromontane grasses, and permanently grazed (Abera, 2006). The remainder indigenous tree species found in the area were *Arundinaria Alpina* and *Juniperus Procera (*Teshome, 2016). However, the land cover of exotic tree species have been increased since adoption in 1980s (Gil et al., 2010), namely the woodlots of eucalyptus, Cupressus, and radiata (Dessalegn & Healey, 2015). The Surra plantation forest is part of the increment of exotic species that were planted during the *Dergue* era by the donation of United Nations Sudano-Sahelian Office (UNSO), African Development Fund (ADF), and World Bank (WB) as part of Ethiopian highlands' plantation project expansion, and that was the golden period of plantation expansion in the history of Ethiopia (Gil et al., 2010).

The economic condition of the people in the upper Hare-Baso rivers catchment is so miserable and is said to be one of the food insecure areas in the Southern region (SNNPRS) of Ethiopia (Mohammed, 2017). For example, mixed high land farming with degraded and highly fragmented farmlands does not sufficiently support the livelihood of the people and is entirely marked as small-scale

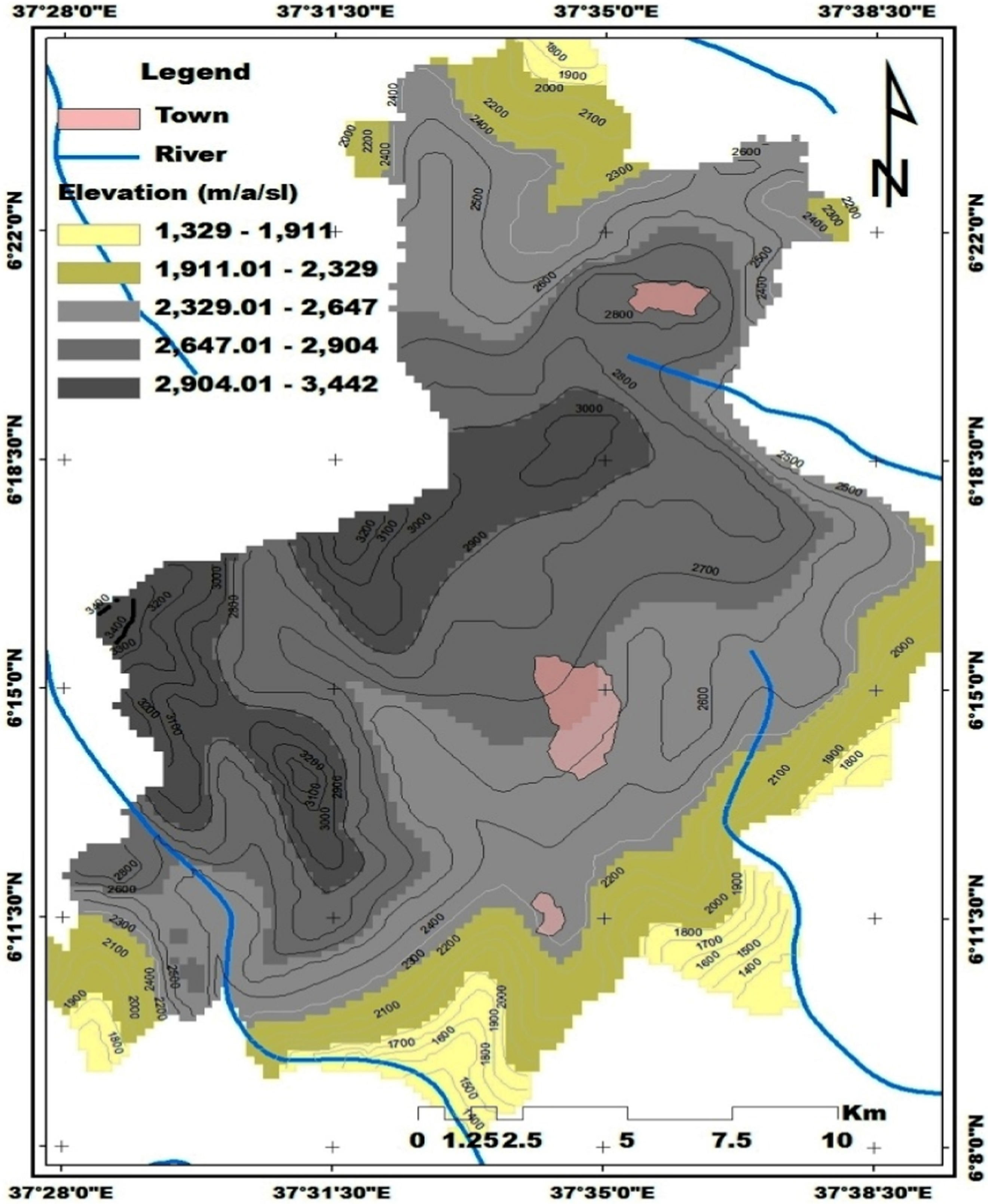

FIGURE 1 The topographic map of Hare-Baso rivers catchment (upper, middle, lower) respect to Hurni's agroecological belt classification of Ethiopia (source: own design via ArcGIS, 2021)

and rain-fed subsistence agriculturists (Teshome, 2015). The farm sizes are extremely marginal and per capita farm holding is less than 0.25 hectares (Mohammed, 2017). The tilling of farmlands using a hoe is dominant over oxen plow because of the scarcity of grazing land and high land fragmentation (Abera, 2006). Since it is a part of the tropical highland agro-climate regions (Hurni, 1998; Kotter et al., 2006) the dominant highland crops such as cereal crops: barley, wheat, peas, and beans; root crops: potato and *enset* (*Enset ventricosum*), and *enset* is the staple foodstuff in the area and part of subsistence agriculture (Jackson, 1968). The traditionally raising of livestock is an integral part of the economy and is practiced by tethering at homestead and gates as well as free grazing at the communal grazing lands. The dominant highland livestock reared are sheep, horses, and cattle (IFPRI, 2012). The subsistence agricultural livelihood is diversified by the petty trade, weaving, and collecting of BLTs from eucalyptus tree species (Abera, 2006). Weaving with its long history in the area is a dominant livelihood diversifying practice take place at home and large cities of Ethiopia (Mohammed, 2017). Moreover, the introduction of apple fruit (suitable for tropical highland climate) is becoming hope for the poor people the area as a source of income (Gebrerufael & Mesfin, 2014).

The Surra plantation forest was planted at a communal grazing land with an average altitude of 3000masl in the mid-1980s (Gil et al., 2010). The total area of the Surra plantation was 235.5 ha, and the component of tree species was *Eucalyptus globulus (*locally *Nech-bahirzaf)*, *Cupressus lusitanica (*locally *Yeferenj tid),* and *Pinus radiata (*locally *Radiata)* (surveyed data, 2021). It was established at the eastern escarpment of the Surra plateau on the mountain Gughe massive with its eastward facing aspects, and relatively confined equidistant from small towns of *Chencha*, *Fango,* and *Ezo* (Figure 1).

2.2 | The research methods

2.2.1 | *Data acquisition methods (field measurement)*

The carbon inventory can be made using ground-based survey method and remote sensing (satellite image and aerial photo) and/or both of them (Pearson et al., 2007; Ravindranath & Ostwald, 2008). However, this study was conducted based on a ground survey technique. The ground-based carbon inventory method was preferably used in this study since this method was thought to be appropriate for the smaller area with tree-dominated forests (Chave et al., 2014; Kangas & Maltamo, 2006; Pearson et al., 2007). Some of the biomass predictor data of trees such as H (height), DBH (diameter at breast height), and WD (wood biomass density) were acquired based on the Condit's data collecting techniques through the ground-based survey (plot method) (Condit, 2008).

The "*plot method*" (a technique of allocating a forest area into manageable sizes in order to accommodate into the desired sample size) is a type of ground-based survey and was used for this study (Pearson et al., 2007; Ravindranath & Ostwald, 2008). Because it is versatile, cost-effective, and applicable to baseline and project scenarios in ground-based carbon inventory techniques (IPCC, 2006; Tadesse, 2015). The "temporary sample plot" method was applied for this study over the permanent sample plot method (Tadesse, 2015). Because the temporary plot method approach is acquired for only a single season of study while the permanent plot method is implemented to study the gain-loss scenario (Ravindranath & Ostwald, 2008).

The parameters' data of H (height) and DBH (diameter at breast height) were acquired via field measurement whereas WD (wood biomass density) of *E. globulus* and *C. lusticana*, as well as P. radiatas' was obtained from different sources (Tesfaye, 2017; Yitebitu et al., 2010). The field survey data of major plot, minor plot, GPS coordinate points, elevation, tree type, date, nature of tree (damaged/undamaged), distance from stand tree, degree of inclination, DBH, and H were collected using "recording sheets"; which was prepared based on the Condit's (Condit, 2008). The tree heights were measured at a preferred distance (10 m from tree bole), except for tree heights less than 7 m, by using the Haglof EC IID clinometer instrument. The EC IID clinometer was applied to set the distance (DIST) (m/ft), inclination/angle (DEG) ($\%/^0$), and height (m) of trees. Tree heights <7 m and >1.3 m were measured by measuring tape, and measuring tape prepared wooden pole. The measuring tape was also used to measure the height of failed trees (*C. lusitanica* and *P. radiata*) in order to estimate the heights of standing trees under the dense cupressus forest to minmize the measuring errors. Most of the height for sampled trees were measured three times being supposed to increase accuracy (Condit, 2008; Návar, 2010).

The DBH exceeding 65 cm was measured by measuring tape (cm), and the DBH ≤65 cm was quantified by a caliper, which is a DBH measuring tool. The DBH of a streight and healthy tree was measured at 1.3 m using a caliper and measuring tape.The DBH measurement took place at 1.3 m (130 cm) from every direction for trees on a gentle slope and downward side for trees on steep slopes (Condit, 2008). The DBH of trees with welling or constriction bole at 1.3 m was measured below the bulged but nearer to the welling, and the trees branched at 1.3 m were measured at the smallest point below it if the stem assumes a nearly cylindrical shape (Pearson et al., 2005). Trees with many buttress (stem) from the ground were measured separately anticipating it would have an insignificant error on the belowground biomass (root-shoot-ratio) results. A tree with 50% of its bole inside the sample plot was measured as part of the sample plot (Ravindranath & Ostwald, 2008).

If trees having multi-stems below 1.3 m height but above the ground were measured by considering each stem separately and was calculated as the square root of the sum of diameters of all stems per plant (Equation 1) (Solomon et al., 2019), and as follows:

$$\boldsymbol{d_e} = \sqrt{\sum_{i}^{n} d_i^2} \tag{1}$$

Where d_e is diameter equivalent (at breast or stump height), and d_i is the diameter of the i^{th} stem at breast or stump height (1.3 cm).

2.2.2 | *The sample size and sampling techniques*

Initially, the total area of the forest was delineated using Garmin-72H Global Positioning System (GPS) with an accuracy of ±3 m in open space and under a dense canopy as well as a cloudy sky (Wing et al., 2005). The area of tree species (*E. globulus*, *C. lusitanica,* and *P. radiata* forest) was re-delineated using GPS and converted into the grid map using ArcGIS version 10.5 (Buja & Charles, 2022) (Figure 2 below).

The square or rectangle shapes of plots are versatile and the most commonly used technique in ground-based biomass and carbon stock survey in most vegetation types (Pearson et al., 2007). The square-shaped sample plots were delineated and selected after determining of sample size, shape, and area of the plots (Condit, 2008; Pearson et al., 2005; Sedjo & Sohngen, 2012). The areas of major and minor plots were determined by considering the recommendations of different scholars (Pearson et al., 2005; Picard et al., 2012; Ravindranath & Ostwald, 2008). The areas of major plots were 100 m*100 m, while minor plots were 10 m*10 m. After determining the sample size and shape of the plots, the grids of major plots were prepared using ArcGIS version 10.5. The sampled size of major plots was drawn out from a grid map using a computer-based simple random sampling procedure (via ArcGIS version 10.5) by considering area proportionality among tree species (Figure 2). The major plots were subdivided into minor plots using ArcGIS version 10.5. Lastly, both maps of major and minor plots were shifted onto the ground using GPS coordinate points (see Figure 2).

The grid map of major and minor plots was copied onto the ground using GPS, the white metal paint, measuring tapes, and threads. Primarily, the centers of major plots were identified and coordinated (northing and Easting) using GPS and coded with white metal paint, and the points were used as a ground control point (GCP) to measure square-shaped major plots (Figure 2). From the GCP, the major plots were manually measured in four directions with a length of 50 m using measuring tape through the center (GCP). Each end of 50 m was coded with a stick and finally extended to the corner that was enabled to create square-shaped plots. The corner was also marked with the stick with the help of Squadra (angle measuring tool) and lastly encircled with string by considering the stability of its square shape so as not to lose or gain standing tree from sampled plots while measurement was conducting (Figure 2) . Thus, the area of tree species considered six and a half (6 ½) major plots was proportionally determined, and were copied onto the ground (i.e., 4 plots of *E. globulus,* 2 *C. lusitanica*, and1/2 *P. radiata)* (Buja & Charles, 2022). The 32 minor plots were determined and sampled purposively from the center and vertices of the major plot and were: 20 eucalyptus, 10 Cupressus, and 2 pinus tree species (Table 1).

2.2.3 | *The data collection techniques*

(a) Estimating aboveground biomass (AGB):

The AGB measuring attributes of trees were H (height), DBH (diameter at breast height), and WD (wood biomass density), and were quantified in order to get AGB (aboveground biomass) of the all tree species. An allometric equation known as the biomass estimation equation was used indirectly to estimate the aboveground biomass (AGB) of trees using abovementioned attributes. But, there is no globally standardized single allometric equation applied to measure the accurate AGB of all tree species by considering different tree growth determining factors (Chave et al., 2005; Gibbs et al., 2007: Picard et al., 2012; Chave et al., 2014). Due to this, most countries have developed their species-specific allometric equations (from DBH and H of trees) to minimize estimating errors. For this study, the species-specific pan-tropical allometric model was implemented to infer the AGB of *C. lusitanica* and *P. radiata* (Chave et al., 2014), while the species-specific allometry equation developed by Tesfaye was used to estimate the AGB of *E. globulus* (Tesfaye, 2017). The Chave's pan-tropical model was preferred as it is the best fit ($\sigma = 0.357$, AIC = 3130, and df = 4002) since there were limitations of a species-specific allometric model developed to estimate biomass of *C. lusitanica* and *P. radiata* tree species in Ethiopia. While the Tesfaye's species-specific allometric equation developed was preferred as it was the best performing model to the eucalyptus tree of the study area at the significance of 97% (with AIC <6, RSE <0.26, and p-value = 0.000) since it was developed for the similar eucalyptus tree species (Tesfaye, 2017). The model of Tesfaye, 2017 is as follows:

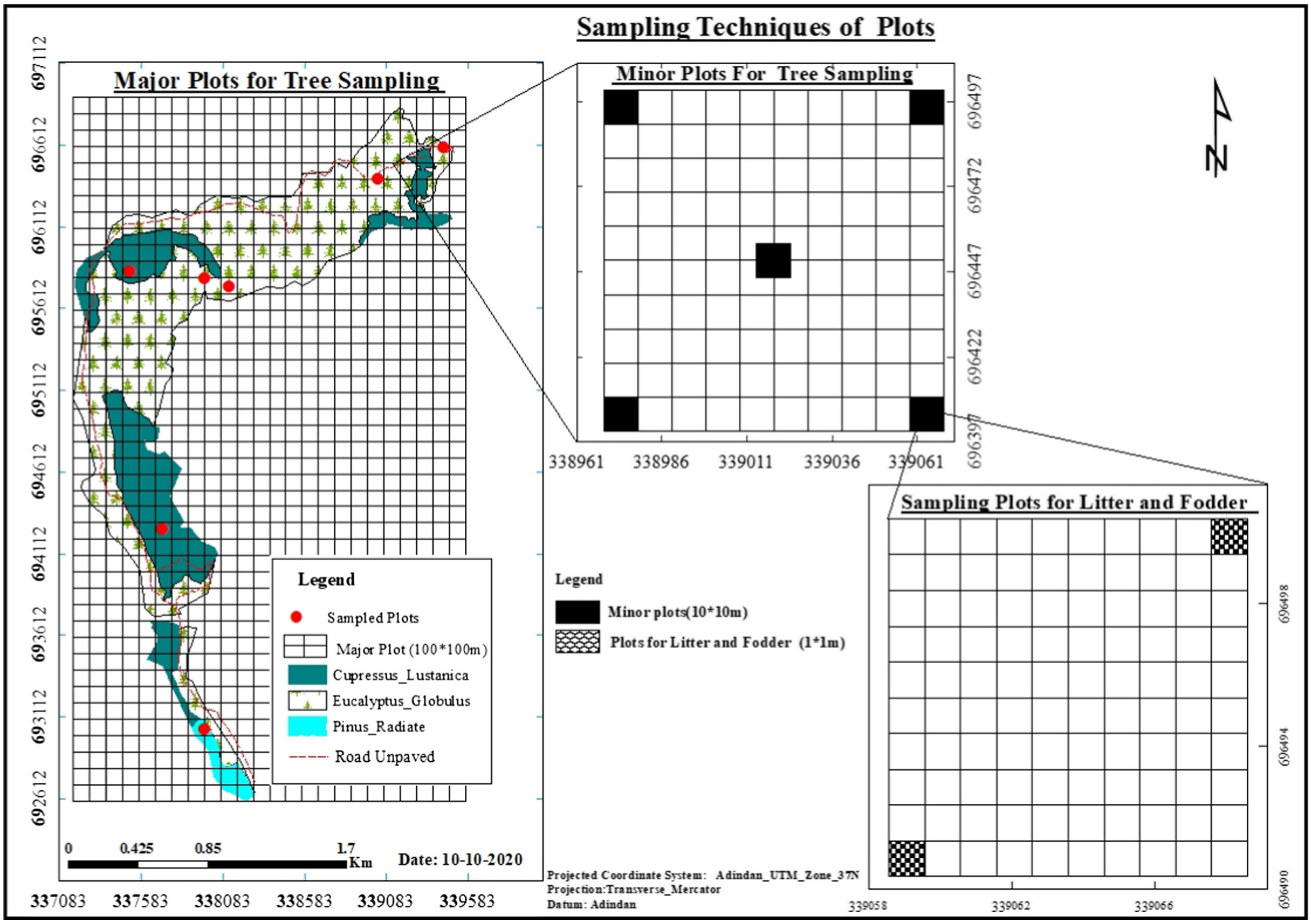

FIGURE 2 Sampling design for major and minor plots to sampling litter (own design using GPS data, 2021)

TABLE 1 Area, location, altitude, slope (^{0}), major and minor plots of the Surra plantation forest

N0	Botanic name (Tree)	Area (ha)	Location (m)		Altitude (m)	Slope (^{0})	Sample plots	
			Northing	Easting			Major	Minor
1	*Eucalyptus Globulus*	172.4	696,612	339,693	3170	7	1	5
			696,412	339,063	3252	12	1	5
			695,512	337,983	3238	9	1	5
			695,732	338,133	3258	8	1	5
2	*Cupressus Lusticana*	57.8	695,832	337,523	3190	6	1	5
			694,262	337,698	3283	9	1	5
3	*Pinus radiata*	5.3	693,062	337,983	3053	3	½	2

Source: Own field survey (2021).

$$AGB_{est} = 0.762^{*}\,(DBH)^{2.2509*}(H)^{-0.449*}(D)^{0.5266} \quad (2)$$

AGBest = estimated aboveground biomass for a live tree (ton/ha), DBH represents diameter at breast height at 1.3 m (cm), H denotes height (m), WD represents wood-specific density (g/cm^3), the exponents of DBH, H and WD are coefficients of the predictors (Tesfaye, 2017). The model of Chave et al., 2014 is as follows:

$$AGB_{est} = 0.\ 0559 * \left(\rho D^2 H\right)^{0.976} \quad (3)$$

AGBest = estimated aboveground biomass of live tree (ton/ha), ρ represents wood density (g/cm^3), D denotes

TABLE 2 Analysis of comparing mean for H and Dbh among tree species

	One-sample *T*-test value					
	T-value	Df	Sig. (2tailed)	Mean difference	95% confidence level	
					Lower	Upper
Height-Radiata	46.636	6	0.000	22.429	21.25	23.61
Height-eucalyptus	20.466	81	0.000	22.332	20.16	24.50
Height-Cupressus	64.141	53	0.000	23.000	22.28	23.72
Dbh-Radiata	27.222	6	0.000	24.2857	22.103	26.469
Dbh-Eucalyptus	15.335	81	0.000	18.5677	16.159	20.977
Dbh-Cupressus	78.701	53	0.000	24.9167	24.282	25.552

Source: The biomass determining attributes of trees were quantified by using SPSS version 20.0 to comparing the mean among tree species.
*Mean Dbh and height of three tree species are significantly different with the $p < 0.05$.

the diameter of a tree at 1.3 m aboveground (cm), and H represents total height (m) (Chave et al., 2014). The wet biomass of forest per kg or ton/hectare of all tree species is depicted in Tables 3 and 4 below.

(b) Estimating belowground biomass (BGB):

If the aboveground biomass (AGB) of a tree species is <50 ton/ha, 50–150 ton/ha and > 150 ton/ha, the belowground biomass becomes 40%/ha, 29%/ha, and 20%/ha of the AGB, respectively (Tolunay, 2011). The belowground biomass of this study was calculated using 20%/ha since the aboveground wet biomass or dry matter of the three tree types (per/ha) was greater than 150 ton/ha (Tolunay, 2011). Even if Tolunay (2011) was developed for temperate tree types, it was preferred to compute the BGB of this study. Because, the Tolunay's approach is relatively specific (depending on the amount of AGB/kg/ha) than others (generic proportionality of AGB; for example,20% is only proportional AGB to BGB/kg/ha) (FAO, 2000; IPCC, 2006). Therefore, the Tolunay (2011) BGB equation was preferred to maximize the estimating accuracy of BGB of the study. The Tolunay, 2011 equation is as follows:

$$BGB = 0.20\ (20\%)^{*} > 150\ (t\,/\,ha) \quad (4)$$

Once AGB and BGB per kg/ha of live trees have got estimated, it is possible to extrapolate to measure the entire forest and each forest patches of tree species biomass that accumulated from planting to the end of the study period as follows (Macías et al., 2017):

$$B_t = \left(\sum AU / 1000 \right) * (TA \text{ or } PA) \quad (5)$$

Where: Bt = entire biomass of all live trees (ton), $\sum AU$ = sum of biomass of trees per unit (hectare) (kg/ha), 1000 = conversion factor of kg to ton, TA = total area of forest (ha), or PA = patch area per tree species (ha). Since the dry matter (DM) of trees is 72.5% of its wet biomass (i.e., 27.5% is moisture), therefore, the "dry weight" was calculated as follows (Macías et al., 2017):

$$D_M = \left(WB_T \right)^{*}\ 72.5\% \quad (6)$$

Where D_W = dry matter, WB_T = wet biomass total, and 72.5% = the dry weight proportion of wet biomass.

(c) Estimation of carbon sequestration:

Since 50% of DM (dry matter) of biomass is a carbon (IPCC, 2006), thus carbon storage of the Surra plantation was computed by multiplying the DM of the forest by 50%, as follows:

$$C_T = \sum DM^{*}\ (50\%\,(0.5)) \quad (7)$$

Where C_T = carbon total; $\sum$ DM = summation of dry matter of different pools (AGB + BGB + litters'); 50% (0.5) = the factors changing the DM into carbon. The litter collected from 40 sample plots (1 m*1 m) of eucalyptus forest, 10 plots from each major plot, was weighed before being oven-dried at 80°C for 48 h and cooled for 1 h (Lee et al., 2020). The oven-dried biomass was weighed and extrapolated into the entire area of the eucalyptus forest (Pearson et al., 2005). To get the carbon content total of the entire eucalyptus tree area, the DM of litter was multiplied by 50% (Viera and Rodríguez-Soalleiro, 2019).

2.2.4 | *The statistical analysis*

The mean height (H) and diameter at breast height (DBH) variation among the three tree species (*E. globulus*, *C. lusitanica,* and *P. radiata)* were considered fixed cases, and each tree was considered a factor. Because, the slope, soil type, age, aspect, and altitude were supposed that there is no significant impact difference between each tree and tree species since tree species are supposed planted on the same plot with more or less similarity in growth determining factors. To analyze the equality of means (comparing means) per hectare (h^{-1}), the *T*-test was implemented by considering 95% confidence; and the significant value at $p < 0.05$ (*), and the result depicts that there were mean variations among tree species namely *E. globulus*, *C. lusitanica,* and *P. radiata* despite area factor (Tables 2 and 4).

3 | RESULTS AND DISCUSSION

The mean value results of the tree biomass determining parameters such as wood-specific density (g/cm^3), H (height), and DBH (diameter at breast height) and its AGB of wet (kg/ha) and total (kg/area of the forest) biomass (AGB) of the forest by tree species are summarized in Table 3. The area of the Surra plantation forest was 235.5 ha, of which eucalyptus covered slightly less than three-fourth (172.4 ha or 73.2%); Cupressus covered nearly one-fourth (57.8 ha or 24.5%) and radiata covered the inconsiderable (5.3 ha or 2.3%) of the total area.

The average standing densities of tree species in the forest were 550 trees/ha (*C. lusitanica)*, 415 trees/ha (*E. globulus*), and 400 trees/ha (*P. radiata*). The estimated average DBH (29.81 cm) and H (26.56 cm) values were the highest for *C. lusitanica* trees, while the corresponding average figures (i.e., DBH = 18.34 cm and H = 22.39 cm) of *E. globulus* trees were the lowest (Table 2). On the contrary, the estimated wood-specific density (WD) was the largest for *E. globulus* trees (0.64 g/cm^3) and the smallest for *C. lusitanica* trees (0.43 g/cm^3). The variations in the average standing tree densities (#/ha), area, mean DBH (cm), mean H (m), and WD (g/cm^3) among tree species have a significant influence on the biomass and carbon storage level of the studied forest (Chave et al., 2014).

The results of wet biomass of *E. globulus*, *C. lusitanica,* and *P. radiata* tree species of the Surra plantation forest are presented in Table 4. The total wet aboveground biomasses of the aforementioned tree species were about 64.7%, 32.8%, and 2.5%, respectively, at the time of the study. The proportions of the three tree species in the total wet belowground biomass (BGB) remained the same as the corresponding shares (%) of the trees in the total aboveground (wet) biomass (IPCC, 2006). The proportion (32.8%) of total wet aboveground (AG) plus belowground (BG) biomass of *C. lusitanica,* relative to its share (24.5%) of area coverage, was larger in comparison with the total wet biomass of eucalyptus, which was 64.7%, and where eucalyptus constituted 73.2% of the total area of the plantation forest (Table 4).

The estimated average aboveground and belowground wet biomass per ha of *C. lusitanica* tree species of the Surra plantation was about 1.5 times the respective average wet biomass of E. *globulus* in the area. In the Surra forest, dissimilarities were observed in the mean values of stems diameter at breast height (DBH) among different tree species having more or less the same age, climate, and location (in one plot), perhaps, due to the variation in tree species given genetic capability, management, and other growth determinant factors (Banaticla et al., 2007; IPCC, 2006; Lee et al., 2020; Tesfaye, 2017). DBH is one of the indicators of variation in biomass of trees of the same and different species (Banaticla et al., 2007; Tesfaye, 2017). A study carried out on manmade forests in Wondo Genet (Ethiopia) revealed that there is species difference-based variation in biomass of trees planted within a single plot, although the variation was insignificant (Yirdaw, 2018). Other studies also showed that almost 35% of the household energy needs of the residents of Addis Ababa city, Ethiopia, were satisfied by about 15,000 women who harvest biomass from the nearby eucalyptus forest (WBISP, 2004; Narita et al., 2018). Thus, domestic energy and other purposes-induced pressure on eucalyptus planted forests could be the main cause for the smaller estimated average biomass of in the Surra plantation forest, in the Gamo highlands of southern Ethiopia.

On the contrary, the total and average dry matter of aboveground and belowground biomass portions of the Surra plantation forest was estimated based on types of tree species, and the results of the estimation are summarized in Table 5. The proportions of aboveground (AG), belowground (BG), and the AG + BG "dry matter" of the

TABLE 3 Mean tree stands/ha, DBH, H, WD, and AG of Wet Biomass of the forest at study period

			Mean/Average			WD	AG biomass	
No	Tree species	Area (ha)	Trees/ha	DBH (cm)	H (m)	(g/cm^3)	Mean (kg/ha)	Total (kg)
1	*E. globulus*	172.4	415	18.34	22.39	0.64	81,857.0	14,112,146.8
2	*C. lusitanica*	57.8	550	29.81	26.56	0.43	295,479.5	17,078,715.5
3	*P. radiata*	5.3	400	23.61	25.56	0.45	64,218.1	340,356.0
	Total	235.5						31,531,218.3

Source: The computed field survey data except wood density (WD) (2021).

TABLE 4 Total wet biomass (kg) and average wet biomass (kg/ha) of both the aboveground (AG) and belowground (BG) portions of the Surra plantation forest upon tree species category

		Total wet biomass (kg)			Average wet biomass (kg/ha)		
Tree species	**Area (ha)**	**AG**	**BG**	**AG + BG**	**AG**	**BG**	**AG + BG**
E. globulus	172.4	14,112,146.8	2,822,429.4	16,934,576.2	81,857.0	16,371.4	98,228.4
(%)	73.2	64.7	64.7	64.7	-	-	-
C. lusitanica	57.8	7,151,287.7	1,430,257.5	8,581,545.2	123,724.7	24,744.9	148,469.6
(%)	24.5	32.8	32.8	32.8	-	-	-
P. radiata	5.3	534,181.7	106,836.3	641,018.0	100,789.0	20,157.9	120,946.8
(%)	2.3	2.5	2.5	2.5	-	-	-
Overall	235.5	21,797,616.2	4,359,523.2	26,157,139.4	92,558.9	18,511.8	111,070.7
(%)	100.0	100.0	100.0	100.0	-	-	-

Source: Own field data (2021). Note: 1 ton = 1000 kg.

TABLE 5 The total and average dry matter (kg/ha) of the aboveground (AG) and belowground (BG) biomass of the Surra forest upon tree species category at the end of the study period

		Total dry matter (kg)			Average dry matter (kg/ha)		
Tree species	**Area (ha)**	**AG**	**BG**	**AG + BG**	**AG**	**BG**	**AG + BG**
E. globulus	172.4	10,231,306.4	2,046,261.3	12,277,567.7	59,346.3	11,869.3	71,215.6
(%)	73.2	64.7	64.7	64.7	-	-	-
C. lusticana	57.8	5,184,683.7	1,036,937.8	6,221,621.5	89,700.4	17,940.1	107,640.5
(%)	24.5	32.8	32.8	32.8	-	-	-
P. radiata	5.3	387,281.8	77,456.3	464,738.1	73,072.0	14,614.4	87,686.4
(%)	2.3	2.5	2.5	2.5	-	-	-
Overall	235.5	15,803,271.9	3,160,655.4	18,963,927.3	67,105.2	13,421.0	80,526.2
(%)	100.0	100.0	100.0	100.0	-	-	-

Source: own field data (2021). Note: 1 ton = 1000 kg.

E. globulus (64.7%), *C. lusitanica* (32.8%), and *P. radiata* (2.5%) tree species remained the same as their area corresponding proportions (%) within the "wet biomass" (Tables 4 and 5). The total aboveground (AG) and belowground (BG) "dry matter" of *E. globulus* was estimated at 64.7% and that of *C. lusitanica* was about 32.8% (Table 5). One important point here is that the estimated (AG + BG) weight of the "dry matter" of each of the three tree species was smaller than its corresponding estimated value of the "wet biomass" by slightly above one-fourth (27.5%) (Table 5).

Alike the "wet biomass," the average aboveground (89,700.9 kg/ha or 89.7 ton/ha), belowground (17,940.1 kg/ha or 17.9 ton/ha), and the overall average (107,640.5 kg/ha or 107.6 ton/ha) of "dry matter" of *C. lusitanica* tree species was significantly larger than the respective average of aboveground (59,346.3 kg/ha 59.3 ton/ha), belowground (11,869.3 kg/ha 11.9 ton/ha), and overall average (71,215.6 kg/ha or 71.2 ton/ha) "dry matter" of *eucalyptus globulus* (Table 4). The average aboveground, belowground, and overall average "dry matter" of *E. globulus* was also by far less than the respective average aboveground (73,072 kg/ha or 73.1 ton/ha), belowground (14,614.4 kg/ha or 14.6 ton/ha), and overall average (87,686.4 kg/ha or 87.7 ton/ha) "dry matter" of *pinus radiata* tree species (Table 5). The overall average (above and belowground) "dry matter" of the manmade forest (i.e., the three tree species) of Surra area per hectare was estimated at 80,526.2 kg/ha or 80.5 ton/ha (Table 5). Another important point here is that the estimated average "below ground" dry matter of each of the three tree species was only one-sixth (16.7%) of the average "aboveground" dry matter of the same tree species.

The significant smaller estimated average biomass was *eucalyptus globulus* than *Cupressus lusitanica* and *pinus radiata* trees (based on our observation at local firewood markets) and was largely a result of the variation in the preference of the local people who tend to harvest eucalyptus more than Cupressus and pinus tree species for construction, energy, and cash purposes. However, the reverse was shown by studies made in central highlands and south-central (Wondo Genet)

Ethiopia where the average tree-stands density and biomass of *eucalyptus globulus* per/hectare were larger than that of *Cupressus lusitanica* and *pinus radiata* tree species since the later tree species were said to be more fascinated by illegal cutters in the area in order to make lumber (Tesfaye et al., 2020; Yirdaw, 2018). Tesfaye et al. (2020) also revealed that about 50–550 ton/ha of eucalyptus plantation tree was lost annually in Ethiopia due to illegal cutting. Since measuring the carbon storage (sequestration) capacity of the Surra plantation forest was one of the objectives of this study, and therefore, the total and average carbon storage capacity of above and belowground biomass of the forest has been quantified, and the results are summarized and illustrated in Table 5 above.

Of the three tree species of Surra forest, *eucalyptus globulus* constituted slightly less than two-thirds (64.7%) of the total aboveground (5115.7 tons), belowground (1023.1 tons), and the sum of AGB + BGB (6138.8 ton) carbon sequestration capacity of the forest. This happened due to the largest share of area coverage (73.2%) among three tree species (i.e., *eucalyptus globulus*) within the manmade forest of the Surra. The *Cupressus lusitanica* and *pinus radiata* tree species accounted for about 32.8% (3115.8 tons) and 2.5% (232.4 tons) of the total (AGB + BGB) carbon stored by the Surra forest since planted to the end of the study period, respectively (Table 5). The estimated total carbon sequestration (AGB + BGB) of the Surra plantation forest (i.e., the three tree species covering the whole study site) was estimated at 9487 tons (Table 5). That is, the total carbon sink (ton) level of the plantation forest from the 1980s (time of planting) to the end of the study period (2021) is relatively low. The estimated average carbon storage ton/hectare level of *eucalyptus globulus* trees (35.6 t/ha) was only about two-thirds (66%) of the average carbon storage of the *Cupressus lusitanica* (53.9 t/ha) and slightly over four-fifth (81.2%) of that of *pinus radiata* tree species (43.8 t/ha) (Table 5). The average aboveground (AG) and belowground biomass (BGB) and average AGB + BGB carbon storage of the whole forest were estimated at 33.6 tons/ha, 6.7 tons/ha, and 40.3 tons/ha, respectively (Table 5).

The estimated average carbon (40.3 t/ha) accumulation of the Surra forest is low compared with the result of other studies (i.e., 106 t/ha) (Justine et al., 2015) due to illegal cutting, frequent grazing, limited conservation, and low protection. Besides, the estimated average and total carbon sink of each of the three tree species is directly proportional to the wet biomass and "dry matter" of each tree species. The difference in average and total biomass and carbon storage level of trees in a single plot with almost the same consignment has emanated from the variations in the tree stand density, DBH, height (H), and wood density (WD) of the trees, and which is similar to the findings of other studies conducted on similar issues (Chave et al., 2014; Macías et al., 2017; Picard et al., 2012).

The litter carbon stock was assessed for *eucalyptus globulus* trees only since the carbon squestrated in the litter of *Cupressus lusitanica* and *pinus radiata* tree species was assumed to be insignificant. Hence, the average litter carbon storage of the *eucalyptus globulus* tree species was estimated at 0.0031 t/ha/year and 0.53ton of total area (172.4 ha) production per annual of eucalyptus forest; and, this was less than the estimated carbon stock of eucalyptus forest litter by other similar studies (Tulu, 2011; Marshet & Teshome, 2015; Viera and Rodríguez-Soalleiro, 2019; Yirdaw, 2018). The frequent harvest of the litter of eucalyptus for household energy use and sale (cash) was one of the main causes of the low litter carbon stock of the Surra plantation forest. Furthermore, illegal cutting at a young age made sparse the standing tree density compared with its early age density, and that enabled the scarce dropping of litter compared with its counterpart studies over eucalyptus plantation forest. Fisher and Binkley (2000) stated that the difference could have come from the variation in the amount of litterfall, the time length of accumulation, and the woody plant type (species, density, and age). For instance, a study showed that the "litter carbon content" of a forest is positively related to the "age" of trees in the forest (Lee et al., 2020).

4 | CONCLUSION AND POLICY OPTIONS

This study has assessed the biomass and carbon sequestration capacity of the Surra plantation forest based on three classes of tree species confined at a single plot such as *eucalyptus globulus*, *Cupressus lusitanica*, and *pinus radiata*. The estimated average "tree height" (m), "diameter at breast height (cm)," and average "stand tree density" (ha^{-1}) were the highest for *Cupressus lusitanica* tree species, while the similar attributes were the smallest for *eucalyptus globulus*. These were due to frequent human pressure on eucalyptus tree species than its counterpart. However, the estimated "wood-specific density" (g/cm^3) was the largest for the *eucalyptus globulus* tree even if all WD data were adapted from other pieces of literature. The average biomass (ton) and carbon sequestration (ton) (ha^{-1}) of *Cupressus lusitanica* trees were significantly larger than that of *eucalyptus globulus* and *pinus radiata* trees. The estimated average biomass (wet and dry) and carbon storage of *eucalyptus globulus* (ha^{-1}) *was* the smallest per hectare. It is supported by statistical analysis and shows that the mean Dbh and height (H) of three tree species (ha^{-1}) vary significantly with a $p < 0.05$. The smallest amount in wet/dry biomass and carbon sequestration of *E. globulus* (ha^{-1}) was due to illegal cutters' preference for the eucalyptus trees for the case of construction, household energy, and cash acquiring over the others. However, total wet/dry biomass and carbon density variation of AGB and BGB occurred among three tree species were determined by their area proportions notably *E. globulus* was the leading with the largest area followed by *C. lusitanica* and *pinus radiata* tree species. Another important point revealed in the Surra plantation forest was the species difference-based significant dissimilarities in the biomass and carbon storage capacity despite the similarities in terms of age, climate, and location (plot) among the three tree species. To conclude that illegal cutting, frequent livestock grazing, and limited conservation and protection were the main causes of the low carbon sequestration of the Surra plantation forest.

Illegal harvesting of tree biomass, the limited commitment to the protection and conservation of the forest, and the use of the forest area for livestock grazing require policy attention (i.e., policy reform and/or change) from the government of Ethiopia so as to improve the carbon accumulation and climate regulation role of the manmade forests.

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CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

DATA AVAILABILITY STATEMENT

The first hand data is in the hands of researchers; Adapted data were formally referenced; Figurs and charts were also referenced.

ORCID

Genesha Mada https://orcid.org/0000-0001-5040-9910

ENDNOTE

Source: Computed from field data (2020, 2021).

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APPENDIX

TABLE A1 Dead litter from 40 sample plots (1 m*1 m) in two seasons (dry and wet seasons), mean weight of dead litter for 2 months per hectare, and weight of entire eucalyptus forest

Wet season kg/40m^2/mon	Dry season kg/40m^2/ mon	Wet kg/ha/ mon	Dry kg/ha/ mon	Mean kg/ha/ mon	Total kg/yr	Ton/yr (year)
1.089	1.275	272.25	318.75	295.5	50,944.2	50.9442

Source: Computed from field data (2020, 2021).