# RESEARCH

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# The impact of land cover change on the carbon stock of moist afromontane forests in the Majang Forest Biosphere Reserve



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# Abstract

**Backgorund** Forest plays an important role in the global carbon cycle by sequestering carbon dioxide and thereby mitigating climate change. In this study, an attempt was made to investigate the effects of land use/land cover (LULC) change (1989–2017) on carbon stock and its economic values in tropical moist Afromontane forests of the Majang Forest Biosphere Reserve (MFBR), south-west Ethiopia. Systematic sampling was conducted to collect biomass and soil data from 140 plots in MFBR. The soil data were collected from grassland and farmland. InVEST modelling was employed to investigate the spatial and temporal distribution of carbon stocks. Global Voluntary Market Price (GVMP) and Tropical Economics of Ecosystems and Biodiversity (TEEB) analysis was performed to estimate economic values (EV) of carbon stock dynamics. Correlation and regression analyses were also employed to identify the relation-ship between environmental and anthropogenic impacts on carbon stocks.

**Results** The results indicated that the above-ground carbon and soil organic carbon stocks were higher than the other remaining carbon pools in MFBR. The mean carbon stock (32.59 M tonne) in 2017 was lower than in 1989 (34.76 Mt) of MFBR. Similarly, the EV of carbon stock in 2017 was lower than in 1989. Elevation, slope, and harvesting index are important environmental and disturbance factors resulting in major differences in carbon stock among study sites in MFBR.

**Conclusions** Therefore, the gradual reduction of carbon stocks in connection with LULC change calls for urgent attention to implement successful conservation and sustainable use of forest resources in biosphere reserves.

Keywords Land use/cover, Carbon stock, Environment and disturbance factors, InVEST model, Africa

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# Background

Forests play an important role in the global carbon cycle, sequestering carbon dioxide  $(CO_2)$  and thereby mitigating climate change [1, 2]. They control climate change by sinking over 200 billion metric tons of carbon a year and converting atmospheric carbon into biomass through photosynthesis [3, 4]. They are significant carbon sinks, accounting for half of the above-ground biomass in vegetation [2, 5]. Moreover, the current carbon stock in global forests is estimated at 861 Gt of carbon, of which 363 and 383 Gt of carbon are stored in the living biomass and soil (up to 1 m), respectively [6–8].

The global carbon cycle has sparked the most interest in recent years as it became clear that rising levels of CO<sub>2</sub> in the atmosphere cause rapid changes in global climate [9, 10]. In the international dialogue, issues such as biodiversity loss, ozone layer depletion, and desertification have taken a central stage [11]. Humans exert significant pressure on the carbon cycle through the use of large amounts of oil, gasoline, and coal, as well as deforestation and land degradation [12, 13]. Deforestation and land degradation are also the major sources of anthropogenic greenhouse gas (GHG) emissions in most tropical countries [14, 15]. Changes in land use/ land cover (LULC) are reducing globally significant carbon storage that is currently sequestering  $CO_2$  from the atmosphere, which makes them critical to long-term climate stability [16, 17]. Every year, tropical deforestation accounts for 15-25% of global GHG emissions [15]. Liu, Van Dijk [18] indicated that between 1993 and 2012, the global Above-Ground Carbon (AGC) declined at a rate of -0.07 PgC/yr due to the loss of tropical forest area. Pan, Birdsey [8] reported that the global soil organic carbon (SOC) decreased by 7.7% (12.7 PgC) between 1990 and 2007, owing primarily to tropical deforestation. Specifically, timber extraction and logging are accountable for over half of forest degradation (52%), followed by fuel wood extraction and charcoal production (31%), induced fire (9%), and overgrazing (7%) in the tropics [19]. This showed that forest degradation and deforestation are the main sources of GHG emissions in most tropical countries.

The InVEST models typically quantify and investigate trade-offs associated with alternative management options as well as indicate areas where natural capital projects can improve land conservation and development [20–22]. InVEST models are spatially explicit (they use maps as input and output) and produce results in either biophysical (e.g., tons of carbon sequestered) or economic terms (e.g., the net present value of that sequestered carbon) [23, 24]. Such a model effectively estimates carbon stock in the landscape ecosystem using carbon pools and LULC classes as input data [25]. Therefore, it provides carbon stock estimates over a large area for trend analysis [21, 26].

Carbon valuation is a monetary estimation of carbon related to small changes in emissions of CO<sub>2</sub> [27, 28]. Carbon valuation is essential for evaluating the relative positive effects of climate mitigation and adaptation policy over time [29–32]. Future carbon benefits are strongly connected to risk management concerns because future values are affected by the chance that benefits may not emerge as expected [33, 34]. Carbon valuation is complicated, and multiple methodologies and sources are used depending on whether a societal or market perspective is used [24, 35]. Although there is no single accepted method for calculating the social value of carbon [30, 36], the Global Voluntary Market Price (GVMP) and Tropical Economics of Ecosystems and Biodiversity (TEEB) databases are used to change carbon stocks as economic terms [37, 38].

Moist Afromontane forests provide a variety of ecosystem services, such as watershed protection, groundwater regulation, food control, prevention of soil erosion, provision of non-timber forest products, and climate change mitigation [39–41]. More specifically, the Majang Forest Biosphere Reserve (MFBR) is one of the recently registered forest biosphere reserves in southern Ethiopia, which is part of the remnants of moist Afromontane forests that continue to provide essential services for people's livelihood [42]. Anthropogenic activities have gradually degraded these moist Afromontane forests over time because they have not been managed sustainably [43–45]. Moreover, estimating changes in carbon stock and its economic value due to changes in forest cover has not been investigated yet. Understanding this encourages decision-makers to create a carbon credit negotiation and sustainable development and conservation of MFBR. Therefore, the aims of this study were "to" (i) examine the change in carbon stocks due to forest cover change over the last 30 years, (ii) map the carbon stock dynamics and its economic value, and (iii) analyse the impacts of environmental and disturbance factors on carbon stocks.

# Methods

### Study area

The study was conducted in the Majang Forest Biosphere Reserve (MFBR), situated in the Majang Zone, *Gambella People National Regional State* of Ethiopia. It has unique biogeography and shares a boundary with Sale Nono Woreda of the Oromia Regional State; Anderacha, Yeki, Sheka, and Gurafereda Woreda of the Southern Nations, Nationalities, and Peoples' Region (SNNPR). It covers a total area of 233,254 ha of forest and agricultural land and rural settlements and towns (Fig. 1). MFBR is located between the latitudes of  $07^{\circ} 08' 00''$  N and  $07^{\circ} 50' 00''$ 



Fig. 1 Location of the study sites (site I–IV) (https://earthexplorer.usgs.gov)

N, and the longitudes of  $34^{\circ} 50' 00''$  E and  $35^{\circ} 25' 00''$  E, with elevations ranging from 562 to 2444 m above sea level (m a.s.l.).

It is distinctive biogeography and shares a boundary with Illubabor Zone of Oromia Regional State; Sheka and Bench-Maji Zones of the Southern Nations, Nationalities, and People Region (SNNPR).

The climate in the area is generally hot and humid, which is marked on most rainfall maps of Ethiopia as the wettest part of the country. The annual average rainfall and temperature are 1774 mm and 22.1 °C, the mean annual minimum and maximum monthly temperature ranges between 13.9 and 31.8 °C in Tinishu Meti metrological station respectively. The annual average rainfall and temperature are 2053 mm and 20.5 °C, the mean annual minimum and maximum monthly temperature ranges between 11.8 and 29.7 °C in Ermichi Metrological station respectively (Fig. 2).

The vegetation in the area is divided into several categories based on its life forms, including high natural forests, woodlands, bush lands, and grasslands. *Euphorbiaceae, Rubiaceae*, and *Moraceae* were the most prevalent families in MFBR, with 13 species (8%), nine genera (7.8%), twelve species (7.4%) and eight genera (7%), and ten species (6.1%), and five genera (4.3%), respectively [46].

### Sampling design

A systematic sampling design was used to arrange quadrats and transects as well as to collect vegetation data [47]. The study area was stratified into four sites using Digital Elevation Model (DEM) in the Arc GIS software. These were site I (<1200 m a.s.l.), site II (1200–1500 m a.s.l.), site III (1500–1800 m a.s.l.) and site IV (>1800 m a.s.l.) (Table 1; Fig. 1). The number of transect lines varied among study sites. A total of 140 quadrats were established for vegetation and forest soil data collection. Farmland (40) and grassland (40) soil samples were acquired from adjoining forestland in each study site of the MFBR.

The study site polygon was digitized using Google Earth by elevation classes. The quadrats' X–Y coordinates were generated using GIS tools and loaded to a global positioning system (GPS) receiver for tracking quadrats. Later, a measuring tape was used to layout  $20 \times 20$  m (400 m<sup>2</sup>) quadrats in each site in the biosphere. The sampling



Fig. 2 Mean monthly temperature and rainfall recorded at a Tinishu Meti (1987–2017) and b Ermichi (1987–2017) (NMSA 2018)

Study site	Ele (m)	Slo (°)	рН	TN (%)	P (ppm)	Area (ha)	SP
Site I	1042±42	$5.3 \pm 0.4$	6.6±0.4	0.32±0.1	16.2±1.1	22,826.1	40
Site II	$1365 \pm 24$	$5.4 \pm 0.4$	$6.3 \pm 0.4$	$0.24 \pm 0.8$	$17.48 \pm 1.4$	25,220.5	45
Site III	$1635 \pm 24$	$7.2 \pm 0.5$	$6.0 \pm 0.5$	$0.14 \pm 0.1$	$19.02 \pm 1.8$	14,053	30
Site IV	$2011 \pm 42$	11.1±1.2	$5.8 \pm 0.4$	$0.11 \pm 0.3$	$20.23 \pm 2.4$	11,783.5	25

Table 1 Topographic and soil characteristics of the study sites

TN total nitrogen, P phosphorus, pH soil pH, Ele elevation, Slo slope, SP sample plots, ppm part per million

intervals between the transect line and the quadrats were 2 km apart. Biomass data for tree census in the tree sites were collected on 5.6 ha (4 sites = 140 quadrats). Aboveground biomass was estimated using a non-destructive sampling method by measuring the diameter at breast height (DBH), tree height, and wood density [48].

### Biomass and soil data collection

During the field data collection, the main carbon measurement activities concerned above-ground tree biomass, below-ground biomass, leaf litter, deadwood, and soil organic carbon. Individual trees with a DBH of >5 cm [49] were measured in each plot with a calliper and measuring tape (at 1.3 m). Each tree was individually recorded, along with its species name and ID. Clinometers and a meter tape were used to measure the heights of all individual trees in the sampling quadrats. Overhanging species were excluded, but trees with trunks inside the sampling plot and branches outside were included [50].

Five rectangular subplots of  $1 \times 1$  m were established at the four corners and centre of each main plot for litter, herbs, and soil data collection. Where the samples were large, the fresh weight of the total sample was recorded in the field, and a manageable-sized (200 g) evenly mixed subsample was brought to the laboratory to determine dry biomass and percentage carbon [51]. The biomass in the pool of leaf Litter, Grass, and Herbs (LGH) was estimated using destructive sampling. Herbaceous samples were collected by clipping and weighing all vegetation before placing it in a sample weighing bag and transporting it to the laboratory to determine the oven-dry weight of the biomass. Forest floor litter materials (dead leaves, twigs, fruit, and flowers) were collected from a 1 m<sup>2</sup> area. The living components, primarily grass and herbs, were harvested and weighed as well. Dry weight was determined in laboratory samples of the materials. Within the 400 m<sup>2</sup> plot, standing dead trees, fallen stems, and fallen branches with a DBH  $\geq$  5 cm were measured [51].

Soil samples were taken with a soil auger from the topsoil at a depth of 0-30 cm, which is recommended as the default sampling depth for soil [52]. Soil samples were taken from five different locations in each plot, four from the quadrat's corners and one from the quadrat's centre. A total of 220 soil samples, 140 from forestland, 40 from farmland, and 40 from grassland were collected, composited separately, labelled, and transported to the laboratory. To determine soil bulk density, the soils were

collected on the centre of the quadrats using a stainless core sampler, then placed in plastic bags, and transported to the laboratory for dry weight determination. Fresh wet soil weights were measured in the field with a kitchen balance with 0.1 g precision. A composite sample of 200 g was taken from each quadrat to analyse its chemical composition [51].

### **Environmental and disturbance factors**

Environmental factors such as aspect, slope, and elevation were measured and recorded for each of the 140 quadrats using a Garmin GPS receiver and clinometers. Elevation was arranged into four elevation (m a.s.l.) ranges (sites I–IV), namely: 1=1200, 2=1200-1500, 3=1500-1800 and  $4 \ge 1800$ . The slope range was classified into three major slope classes following [53]. As a result, the classes were: (1) flat < 10, (2) intermediate 10–20, and (3) steep > 20.

The human disturbance (which includes harvesting trees for fuel, wood, charcoal, timber, and house construction) was computed as the harvesting index. The harvesting index was measured by counting individual stumps, which reflected illegally logged trees, within the quadrat and calculated from the relative density of individual tree stumps. The relative density of stumps was computed as the sum of stump density divided by the total density (the sum of the logged stump and living individual trees). Stumps are a small portion of the trunk that remains after a tree with about 5 cm diameter is chopped down [54].

## Spatial data analysis

## Land use/land cover data

The LULC types and Tag Image File Format (TIFF) data were obtained from a previously published article by Tadese, Soromessa [55]. They included area statistics for five different land cover types for the years 1987, 2002, and 2017 (Table 2).

The spatial distribution of carbon stock pools in different LULC types for each study year (forest land, farmland, and grassland) were analysed using the InVEST model (Fig. 3).

Table 2 Area of LULC classes from 1987 to 2017 in MFBR adopted from Tadese et al. [46]

LULC classes	1987		2002		2017	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Forestland	196,761.6	84.4	188,413.7	80.8	181,504.9	77.8
Farmland	30,781.8	13.2	36,906.4	15.8	40,554.8	17.4
Grassland	3509.2	1.5	3079.6	1.3	3192.2	1.4
Settlement	2050.7	0.9	4744.3	2.0	7866.2	3.4
Water body	141.0	0.06	141.0	0.06	141.0	0.06
Total	233,254	100%	233,254	100%	23,3254	100%



Fig. 3 Flow chart of the methodology

### Carbon stock estimation using the InVEST model

The InVEST modelling framework is a set of opensource models for mapping and valuing the goods and ecosystems that produce the flow of services required to sustain life on Earth [21, 56, 57]. We customised the InVEST carbon stock mapping and sequestration model to assess the amount of total carbon stored in the five carbon pools (above-ground biomass, belowground biomass, deadwood, litter, and soil organic matter) in different LULC classes of the study area. Carbon stock values were assigned to each LULC class for the selected years (i.e., 1987, 2002, and 2017) using field inventory data for forest land, farmland, and grassland.

To meet the model's requirements, the LULC and carbon pool data sets were prepared and used as the primary input data to estimate carbon storage in each grid cell. Land use codes, the name of the LULC class, the amount of Above-Ground Biomass (AGB), Below-Ground Biomass (BGB), deadwood (DW), Litter, Grass, and Herbs (LGH), and Soil Organic Matter (SOC) are all included in the carbon stock data set in an MS Excel database. The LULC class is encoded with land-use codes in each row. Except for settlements and water bodies, which have zero carbon stock in all carbon pools, each column contains different attributes of the LULC type. Carbon in each pool was then combined across land-use types to estimate the total carbon storage.

### Soil laboratory analysis

The soil samples were analysed in the Water Works Design and Supervision Enterprise laboratory (WWDSE) in Addis Ababa, Ethiopia. The Bouyoucos Hydrometer Method was used to determine the soil textures (expressed as a percentage of weight). It is a particle size analysis method that calculates the physical proportions of soil particles based on their settling rates in an aqueous solution [58]. Soil pH was determined using a pH meter and a 1:2.5 soil to water suspension potentiometric method [59]. The Micro-Kjeldahl [60] and Walkley and Black [61] methods were used to determine total nitrogen (N) and soil organic carbon, respectively. The Bray-I method was used to determine available phosphorus, and the absorbance of the Bray-I extract was measured in a spectrophotometer at an 882 nm wavelength [62]. Based on C and N concentrations, the Carbon to Nitrogen ratio (C/N) was calculated. The mass of each soil sample (MS) was determined using oven-drying set to 105 °C for 24 h to achieve a constant weight [49]. The volume of the Core Sampler (VC) was determined as VC =  $\pi$  r<sup>2</sup>h, where r is the radius and h is the height of the core sampler  $(VC = 3.14 \times (2.5 \text{ cm})^2 \times 5 \text{ cm} = 98.125 \text{ cm}^3).$ 

### Carbon stock and value analysis

Data analysis of various carbon pools measured in the forests was performed in R version 4.0.1. [63]. The AGB of trees was calculated using a previously published allometric equation in which the independent variables were trunk diameter (D, cm), height (H, m), and wood density (p, g cm<sup>-3</sup>) (predictors) [64]. The Global Wood Density database was used to determine the wood density of different species [65]. The following formula [64] was employed to calculate the above-ground biomass with the BIOMASS package in R [66]:

AGB (kg) = 
$$0.0673 * (pD^2H)^{0.976}$$
, (1)

where *AGB* is the above-ground biomass of trees (kg), p is the specific wood density (g cm<sup>-3</sup>), D is the trunk diameter at breast height (cm), and H is the total height of trees (m). The total AGB carbon for each quadrat was calculated as aggregate AGB carbon for all trees. Carbon stocks were determined for each quadrat and then extrapolated to tonnes per hectare. The carbon content in AGB is calculated by multiplying the default carbon fraction by 50% [67].

Below-ground biomass was estimated with the equation developed by [50]

$$BGB = AGB * 0.2, \tag{2}$$

where *BGB* is below-ground biomass, *AGB* is aboveground biomass, 0.2 is the conversion factor (or 20% of AGB).

For standing deadwood (SDW) which has branches, the biomass was estimated using the allometric equation for the estimation of above-ground biomass [51].

For the remaining standing deadwood, the biomass was estimated using wood density and volume calculated from the truncated cone [51].

Volume (m)<sup>3</sup> = 
$$\frac{1}{3}\pi h r_1^2 + r_2^2 + r_1 * r_2$$
, (3)

where *h* is the height in meters,  $r_1$  is the radius at the base of the tree, and  $r_2$  is the radius at the top of the tree.

$$Biomass = Volume \times Wood density (from samples).$$
(4)

The biomass of lying deadwood was estimated by the equation given below [51].

$$LDW = \sum_{i=1}^{n} V * S,$$
(5)

where *LDW* is lying dead wood, *V* is volume, and *s* is the specific density of each density class.

The lying deadwood volume per unit area is estimated with:

$$V = \pi^2 \left( \sum \frac{D1^2 + D2^2}{8L} \right),\tag{6}$$

where *V* is the volume in  $m^3/ha$ ; *L* is the length of the line transect, and *D* is the diameter of the deadwood tree. The carbon content in AGB is calculated by multiplying the default carbon fraction by 50% [67].

The biomass in the pool of leaf litter, grass, and herbs was estimated using destructive sampling. Forest floor litter material (dead leaves, twigs, fruit, and flowers) was collected from a 1 m<sup>2</sup> area. The living components, primarily grass and herbs, were harvested and weighed as well. Dry weight was determined in laboratory samples of the material. To estimate the biomass carbon stock of the litter, 100 g of fresh litter subsample was taken for laboratory use, and each sample was then dried in an oven at 105 °C for 24 h to obtain the dry weight [51].

The leaf litter, grass, and herbs (LGH) biomass per hectare was computed using the following formula:

$$LHG = \frac{W_{field}}{A} \times \frac{W_{sub\,sample,\,dry}}{W_{sub\,sample,\,wet}} \times \frac{1}{10,000},$$
 (7)

where *LHG* is the leaf litter, herbs, and grass biomass (tonne ha<sup>-1</sup>),  $W_{field}$  is the weight of fresh leaf litter, herbs, and grass sampled destructively within area A (g), A is the size of the area where leaf litter, herbs, and grass were collected (ha),  $W_{subsample'}$  dry is the weight of oven-dried sub-sample of leaf litter, herbs, and grass taken to the laboratory for moisture content determination (g),  $W_{sub-sample'}$  wet is the weight of fresh sub-sample of leaf litter, herbs, and grass taken to the laboratory for moisture content determination (g).

Carbon stocks in litter biomass were calculated using the following formula:

$$CL = LHG * \%C, \tag{8}$$

where *CL* is the total carbon stocks in litter in tonne ha<sup>-1</sup>, *LHG* is the leaf litter, herbs, and grass biomass (tonne ha<sup>-1</sup>) and % *C* is the carbon fraction determined in the laboratory [51].

The soil carbon stock was assessed in this study using the fine soil fraction to a depth of 30 cm. The following equation was used to calculate the bulk density (BD):

$$BD = \frac{MS}{VC},$$
(9)

where *BD* is the bulk density (g cm<sup>-3</sup>), *MS* is the mass of the oven-dry soil (g) and *VC* is the volume of the core sampler (cm<sup>3</sup>).

The amount of carbon stored per hectare was calculated using the following formula, taking into account soil depth (cm), bulk density (g cm<sup>-3</sup>), and the percentage of

soil organic carbon content (SOC), which is the recommended method [51].

$$SOC = BD \times d \times \%C, \tag{10}$$

where *SOC stock* is the soil organic carbon stock per unit area (tonne ha<sup>-1</sup>), *BD* is the bulk density (g cm<sup>-3</sup>), *d* is the total depth of the sample (30 cm), and % *C* is the soil organic carbon concentration (ppm).

The carbon stock density of each stratum was calculated by aggregating the carbon stock densities of each stratum's carbon pools using the formula in the following equation.

$$C (LU) = C (AGB) + C (BB) + C (DWB) + C (LHG) + SOC,$$
(11)

where C (*LU*) is the carbon stock density for a land-use category (C t ha<sup>-1</sup>), C (AGB) is the carbon in aboveground tree components (C t ha<sup>-1</sup>), C (BB) is the carbon in below-ground components (C t ha<sup>-1</sup>), C (DWB) is the carbon in deadwood tree components (C t ha<sup>-1</sup>), C (*LHG*) is the carbon in the litter, herbs, and grass (C t ha<sup>-1</sup>), SOC is the soil organic carbon (C t ha<sup>-1</sup>).

Carbon was summed, and the total was then multiplied by 44/12 (3.67) to convert it into the carbon dioxide equivalent.

A chronological carbon storage change investigation was conducted at MFBR for the reference years 1987, 2002, and 2017 according to the method proposed by [68]. After calculating the carbon stock and value based on the previous, baseline year in the MFBR, change was analysed using the below equation.

$$\Delta C = \frac{C_{Final year} - C_{initial year}}{C_{initial year}} * 100\%, \tag{12}$$

where  $\Delta C$  is the percentage change in carbon,  $C_{final year}$  is the carbon stock in the final (recent) year, and  $C_{initial year}$  is the carbon stock in the initial years.

# Carbon market value estimation *Global voluntary market price*

The global voluntary market price of carbon sequestration was compared using two data sources: the Global Voluntary Market Price (GVMP) and Tropical Ecosystems and Biodiversity (TEEB) database valuation. The carbon storage rate for the landscape is necessary to determine carbon sequestration (CO<sub>2</sub>e) in the GVMP set by different actors, such as the World Bank. The carbon storage rate (t ha<sup>-1</sup>) multiplied by 3.67 (44/12=3.67) is used to estimate CO<sub>2</sub>e [49]. Hence, the sequestered carbon (CO<sub>2</sub>e) is multiplied by the market price of carbon storage (4.40 USD/tCO<sub>2</sub>e) which was the carbon credit used in the Clean Development Mechanism (CDM) project under the Humbo forest rehabilitation in Ethiopia [69, 70]. To analyse the monetary value, the annual rate of change in the carbon price of 3% and the market discount rate of 7% was required to estimate carbon storage value. The total value of carbon stock has been estimated by the sum of each land-use type area multiplied by the monetary value of its carbon stock.

### **TEEB carbon valuation data**

The Tropical Ecosystems and Biodiversity (TEEB) database (http://www.teebweb.org) contains the monetary value of carbon sequestration for various land-use types [71]. The TEEB data were collected from different parts of the biome and analysed using different methods such as direct market pricing, avoided cost, and benefit transfer [37, 38]. These valuation data were adapted to East Africa to compare the carbon sequestration values for MFBR (Table 3). The total carbon value was calculated by multiplying the area (ha) of each LUC type by its corresponding value of CO<sub>2</sub>e for that particular LULC type [39, 72].

In other words, the value of  $Co_2e$  obtained from TEEB multiplied by the LULC area yields the total market value of carbon. The carbon stock value data obtained from the TEEB database has been rearranged (sorted, summed, filtered by region, etc.) for supplementary analysis.

The carbon stock value was estimated based on two approaches. In the first approach, the carbon stock value was estimated using GVMP (4.40 USD in 2019), which is considered a discount rate (7%) and the annual rate of change in the carbon price (3%).

It was calculated using the following equation:

$$TCV = CS (5 \text{ pools}) t/ha$$
  
\* Area (ha) \* CP (\$/tonne) - DR + ARC, (13)

where *TCV* is the total carbon value, *CS* is the carbon stock in five pools, *CP* is the carbon price per tonne, *DR* is the discount rate, and *ARC* is the annual rate of carbon price change.

In the second approach, the carbon stock value was estimated using the TEEB database, which contains carbon sequestration values for each LULC type (Table 3).

It was calculated using the equation below:

**Table 3** Carbon sequestration value for each LULC type in theTEEB database

No.	LULC	Carbon sequestration prices (USD/ha/yr)
1	Forest land	1229.79
2	Grazing land	297
3	Farmland	96

TCV = CS (5 pools) t/ha \* Area (ha) \* CP of LUC type (\$/tonne),(14)

where *TCV* is the total carbon value, *CS* is the carbon stock in five pools, *CP* is the carbon price for each LUC type per tonne.

## Statistical analysis

One-way ANOVA was used to determine whether there were significant differences between environmental and disturbance factors regarding carbon stocks in R software [63]. The statistical significance level was set at 5%. Pearson correlation analysis was used to examine the relationship between environmental-disturbance factors regarding carbon stocks. When the value of r approaches negative 1, the carbon stock and the independent variable (factors) are inversely proportional (carbon stock increases as the factors decrease). If r approaches positive 1, the carbon stock increases while the factors increase.

### Results

## Carbon stock in carbon pools

In the MFBR, the mean above-ground carbon (AGC) and below-ground carbon stocks (BGC) in the forest land were 272.57 and 54.97 t  $ha^{-1}$ , respectively (Table 4). The minimum and maximum of the mean AGB carbon stock were 144.21 and 661, while BGB carbon stocks were 28.84 and 155.81 t ha<sup>-1</sup> in MFBR, respectively. The distribution patterns of the BGB carbon stock showed similar trends to those of the AGC stock. The mean dead wood and litter, herbs, and grass carbon (LHGC) stocks were 3.04 t ha<sup>-1</sup> and 0.05 t ha<sup>-1</sup>, respectively. The minimum and maximum deadwood carbon (DWC) stocks were 0.13 and 6.11 t ha<sup>-1</sup>, while litter, herbs, and grass LHGC stocks were 0.016 and 0.32 t  $ha^{-1}$ , respectively. The mean soil organic carbon (SOC) stock was 176.26 t ha<sup>-1,</sup> and the minimum and maximum SOC stocks were 116.96 and 280.31 t ha<sup>-1</sup> respectively (Table 4).

The mean carbon stock in the carbon pool increased from site one to site four. The mean AGC stock varied among the four study sites of the MFBR, ranging from  $260.8 \pm 8.5$  to  $282.0 \pm 15.1$  t ha<sup>-1</sup>. The soil carbon pool has a significant contribution to the total carbon stock of MFBR. The SOC of MFBR fluctuated among the study sites; site four contributed the highest SOC (199.3 \pm 7.1 t ha<sup>-1</sup>), followed by site one (178.6 \pm 5.1 t ha<sup>-1</sup>). The smallest amount of soil carbon was obtained for site one (161.0 ± 2.1 t ha<sup>-1</sup>) (Table 4). The mean forest SOC stock in MFBR increased with elevation from study site one to four, ranging from 161.0 ± 2.1 to 199.3 ± 7.1 t ha<sup>-1</sup>, respectively, (Table 4). Similarly, the mean SOC for farmland and grassland increases with elevation and varies from 128.6 ± 5.8 to 135.8 ± 2.7 and from 145.7 ± 5.4 to

Carbon pool	Study sites				
	Site I	Site II	Site III	Site IV	Mean TCS (MFBR)
AGC	269.7±7.3	260.8±8.5	277.9±20.0	282.0±15.1	272.57
BGC	$53.9 \pm 1.5$	$50.6 \pm 1.6$	$55.6 \pm 4.1$	$59.7 \pm 4.1$	54.97
DWC	$2.4 \pm 0.2$	$2.7 \pm 0.1$	$3.3 \pm 0.3$	3.8±0.27	3.04
LHGC	$0.03 \pm 0.01$	$0.04 \pm 0.02$	$0.05 \pm 0.01$	$0.08 \pm 0.01$	0.05
FoSOC	$161.0 \pm 2.1$	$166.2 \pm 2.7$	$178.6 \pm 5.1$	$199.3 \pm 7.1$	176.26
Falsoc	$128.6 \pm 5.8$	$129.1 \pm 4.1$	131.1±6.3	$135.8 \pm 2.7$	131.16
GLSOC	$145.7 \pm 5.4$	$154.0 \pm 6.7$	$148.0 \pm 5.6$	$148.8 \pm 4.1$	149.09
TCS	$761.3 \pm 9.5$	$763.3 \pm 10.5$	$794.5 \pm 24.6$	$829.4 \pm 26.2$	787.14
CO <sub>2</sub> Seq.	$2794.0 \pm 35.1$	$2801.5 \pm 38.5$	$2915.7 \pm 90.5$	$3043.9 \pm 25.6$	2888.79

Table 4 Total carbon stocks and CO<sub>2</sub> sequestration (t/ha) in four study sites

Site I  $\leq$  1200, site II = 1200–1500, site III = 1500–1800, and site IV  $\geq$  1800 m a.s.l.

AGC above ground carbon, BGC below ground carbon, DWC dead wood carbon, LHGC litter, herbs and grass carbon, FoSOC forest soil organic carbon, FaLSOC farmland soil organic carbon, GLSOC grassland soil organic carbon, TCS total carbon stock



Fig. 4 Total carbon stock in t ha<sup>-1</sup> and tCO<sub>2</sub>e t ha<sup>-1</sup> for each plot

148.8 ± 4.1 t ha<sup>-1</sup>, respectively. In comparison, the total carbon stock stored in forest biomass was higher than in grassland and farmland in the MFBR. The overall mean total carbon stocks and sequestration for all LULC types were 787.14 t ha<sup>-1</sup> and 2888.79 t CO<sub>2</sub>e ha<sup>-1</sup>, ranging from 761.3 ± 9.5 to 829.4 ± 26.2 t ha<sup>-1</sup> for carbon stocks and from 2794.0 ± 35.1 to 3043.9 ± 25.6 t CO<sub>2</sub>e ha<sup>-1</sup> for carbon sequestration, respectively, along the elevation gradient in MFBR (Fig. 4).

The total AGC stocks of five dominant species in four study sites are shown in (Table 5). In study site I, the total AGC stock of the first five species 119.4 t ha<sup>-1</sup> (44.8%). The highest AGC stock was contributed by *Cordia Africana* (41.2 t ha<sup>-1</sup>) followed by *Combretum molle* (28.3 t ha<sup>-1</sup>) *and Lecaniodiscus fraxinifolius* (22.3 t ha<sup>-1</sup>). The first five species of the total AGC stock amounted to 138.9 t ha<sup>-1</sup> (55.1%) in study site II. The highest AGC stock was found for *Fagaropsis angolensis* (45.9 t ha<sup>-1</sup>),

followed by *Albizia grandibracteata* (30.1 t ha<sup>-1</sup>), and *Cordia africana* (25.4 t ha<sup>-1</sup>). The total AGC stock of the first five species was 120 t ha<sup>-1</sup> (46%) in site III. The highest mean AGC stock was contributed by *Cordia Africana* (38.0 t ha<sup>-1</sup>), followed by *Ficus mucuso* (28.7 t ha<sup>-1</sup>) and *Croton sylvaticus* (21.5 t ha<sup>-1</sup>). The total AGC stock of the first five species contributed 90.3 t ha<sup>-1</sup> (35.1%), in study site IV. The highest AGC stock was contributed by *Allophylus abyssinicus* (29.2 t ha<sup>-1</sup>), followed by *Prunus africana* (16.9 t ha<sup>-1</sup>), and *Ficus sur* (12.3 t ha<sup>-1</sup>) (Table 5).

In this study, DBH classes are directly related to the AGC stock while inversely related to trunk density per hectare. The trunk density of smaller-sized classes is higher than that of larger-sized classes, although they contribute a smaller amount of AGC stock per hectare. Moreover, the larger trunk diameter classes (DBH  $\geq$  40) showed higher AGC stock in site I (60.9%), site II (63.1%), site III (61.4%), and site IV (63.1%) as compared to smaller trunk diameter classes (DBH  $\leq$  40) (Fig. 5). Therefore, the amount of AGC stock increased with DBH, which indicated that harvesting larger-sized trees leads to carbon stock reduction. The density per hectare decreases with an increase in DBH classes.

Above-ground carbon stock showed a strong positive correlation with DBH classes(r=0.85 and P=0.05), while density per hectare showed a strong negative correlation with DBH classes (r = -0.89 and P=0.05).

# Carbon stock in land use/land cover

Above-ground biomass carbon (272.57 t ha<sup>-1</sup>) had the highest carbon pool in the forest land followed by SOC (176.26 t ha<sup>-1</sup>), while LHG biomass (0.05 t ha<sup>-1</sup>) had the lowest carbon pool (Table 6). The shares of carbon pools in forest land were the following: the AGC (53.77%), BGC (10.84%), DWC (0.59%), LHGC (0.009%), and SOC

Species	WD	DBH	н	Ind	AG-C	% AG-C
Site I						
Cordia africana	0.54	35.2	26.8	22	41.2	15.3
Combretum molle	0.73	29.1	30.8	14	28.3	10.7
Lecaniodiscus fraxinifolius	0.73	25.8	21.4	26	22.3	8.4
Morus mesozygia	0.72	23.7	19.3	8	15.4	5.8
Manilkara butugi	0.95	24.1	20.4	9	12.2	4.6
Site II						
Fagaropsis angolensis	0.57	44.8	37.2	12	45.9	18.2
Albizia grandibracteata	0.46	45.7	32.0	6	30.1	11.9
Cordia africana	0.54	33.2	24.5	43	25.4	10.1
Mimus opslanceolata	0.86	41.2	31.2	10	20.7	8.2
Grewia mollis	0.82	24.4	24.6	27	16.8	6.7
Site III						
Cordia africana	0.54	42.1	34.0	40	38.0	14.7
Ficus mucuso	0.44	28.2	21.9	14	28.7	11.1
Croton sylvaticus	0.64	26.2	27.8	20	21.5	8.3
Apodytes dimidiata	0.61	19.7	17.3	28	17.8	6.9
Blighia unijugata	0.56	23.6	21.8	42	13.0	5.0
Site IV						
Allophylus abyssinicus	0.61	28.3	25.0	34	29.2	11.3
Croton macrostachyus	0.52	26.8	25.8	8	21.1	8.2
Prunus africana	0.69	27.1	25.0	26	16.9	6.6
Ficus sur	0.41	32.1	25.3	10	12.3	4.8
Trilepisium madagascariense	0.50	28.7	24.4	49	10.8	4.2

Table 5 Mean above-ground carbon stocks in five dominant species in four study sites

WD wood density (g cm<sup>-3</sup>), DBH diameter at breast height (cm), H height (m), Ind individual number, AG-C above-ground carbon (t ha<sup>-1</sup>)

(34.77%). In general, the highest contribution came from AGC, followed by SOC, BGC, and DWC. In comparison, SOC stock in forest land (176.26 t  $ha^{-1}$ ) was higher than for grassland (149.09 t  $ha^{-1}$ ) and farmland (131.16 t  $ha^{-1}$ )



Fig. 5 Density and AG carbon stock along DBH classes in MFBR. A  $\leq$  10, B = 10.1–20, C = 20.1–30, D = 30.1–40, E = 40.1–50, F = 50.1–60, and G  $\geq$  60 cm

(Table 6). Thus, the contributions of SOC were (22.39%), (18.94%), and (16.66%) in forest land, grazing land, and farmland, respectively. The AGC, BGC, and DWC pools were not estimated on grassland and farmland due to the absence of trees exceeding 5 cm DBH in the study plots (Table 6).

Above-ground carbon, BGC and DWC amounted to about 34.62%, 6.98%, and 0.38% of forest land storage, respectively. The share of LHGC was 0.006% in the forest land and grassland. Likewise, there was no significant contribution from the water body and settlement (Table 6).

### Effects of land cover change on carbon stock

The LULC affected the carbon stock during the 1987 to 2017 period in MFBR (Table 7). The maximum carbon stock was found in forest land (99.73 million tonne) followed by farmland (4.03 million tonne), whereas the lowest was identified in grassland (0.52 million tonne) in 1987 of MFBR (Table 7). Similarly, the maximum carbon stock was shown in forest land (92.01 million tonne) followed by farmland (5.32 million tonne) whereas the lowest was identified in grassland (0.47 million tonne)

LULC	AGC	BGC	DWC	LHGC	SOC	Total
FoL	272.57	54.97	3.04	0.05	176.26	506.88
FaL	0	0	0	0	131.16	131.16
GL	0	0	0	0.001	149.09	149.09
Set	0	0	0	0	0	0
WB	0	0	0	0	0	0
Ave				0.055	152.17	152.225

Table 6 Carbon pools by land use/land cover (t/ha)

AGC above ground carbon, BGC below ground carbon, DWC dead wood carbon biomass, LHGC litter, herbs, and grass carbon, SOC soil organic carbon, FoL forestland, FaL farmland, GL grassland, Set settlement, WB water body, Ave average

Table 7 Carbon storage and its changes in the reference years (million t/ha and CStCO<sub>2</sub>e/ha)

LUC	1987		2002		2017		Change (1987–2017)	
	CS t ha <sup>-1</sup>	CStCO <sub>2</sub> e ha <sup>-1</sup>	CS t ha⁻¹	CStCO <sub>2</sub> e ha <sup>-1</sup>	CS t ha <sup>-1</sup>	CStCO <sub>2</sub> e ha <sup>-1</sup>	CS t ha <sup>-1</sup>	CStCO <sub>2</sub> e ha <sup>-1</sup>
FoL	99.73	366.02	95.50	350.49	92.01	337.64	-7.73	- 28.28
FaL	4.03	14.82	4.84	17.76	5.32	19.52	1.28	4.70
GL	0.52	1.92	0.45	1.68	0.47	1.75	-0.04	-0.17
Ave	34.76	127.58	33.60	123.31	32.59	119.63	-2.16	- 7.9

CS t ha<sup>-1</sup>: carbon stock ton per ha; CStCO<sub>2</sub>e ha<sup>-1</sup>: carbon stock ton carbon dioxide equivalent per ha; FoL: forestland; FaL: farmland; GL: grassland; Ave: average

in 2017 of MFBR. Based on the InVEST carbon model results, the conversion of forest land and grassland into farmland led to a reduction of carbon stock in MFBR (Figs. 6 and 7). The chronological investigation indicated that the carbon stock declined by 7.73 million tonne in forest land from 1989 to 2017, while the average carbon stock was reduced by 2.16 million tonne with an annual loss of 0.07 million tonne. The drop in the carbon stock is due to the reduction of forest land and grassland from 1987 to 2017 in MFBR.

In forest land, the total carbon stock shrunk from 366.02 million tonne  $CO_2e$  in 1987 to 337.64 million tonne  $CO_2e$  in 2017 of MFBR. Forest land and grassland cover declined with 6.6% and 0.1%, respectively, which led to a reduction of 28.38 million and 0.17 million tonne  $CO_2e$  in the previous 30 years respectively of MFBR (Table 7). The average carbon stock was diminished by 7.9 million tonne  $CO_2$  with an annual loss of 0.26 million tonne  $CO_2$ , which is due to the reduction of forest land and grassland from 1987 to 2017 in MFBR (Table 7). In general, changing LULC classes reduce vegetation cover, which directly contributes to increased or reduced carbon sequestration and carbon market value.

## Carbon storage valuation

The global voluntary market price analysis showed that the average carbon sequestration was reduced from \$5.55 billion in 1987 to \$5.21 billion in 2017 in MFBR. In other words, the mean carbon value shrunk \$0.011 billion t/ha/year over the previous 30 years. Forest land was the most important carbon-sequestering land-use class. However, the value of carbon sequestration decreased by \$0.071 billion t/ha/year from \$16.84 billion in 1987 to \$14.70 billion in 2017 (Table 8).

According to the carbon sequestration monetary value analysis of TEEB, the mean value of carbon sequestration went down from \$1515.62 billion in 1987 to \$1403.89 billion in 2017. The TEEB carbon sequestration value estimation (\$1403.89 billion) is greater than that of GVMP (\$5.21 billion) in 2017 (Table 8). This significant carbon value variation between GVMP and TEEB indicated a gap in carbon value estimation methods. Furthermore, the use of different methods of carbon pricing led to uncertainty in the estimation of carbon sequestration value.

Based on the estimation of TEEB and GVMP, carbon sequestrations for forest and grassland values have been drastically reduced as a result of human disturbances like vegetation. The TEEB and GVMP analyses estimated the carbon value of forest land to decline by \$34.9 billion (7.75%) and \$2.14 billion (12.70%), respectively, while grassland declined by \$0.01 billion (5.55%) and \$0.0007 billion (8.04%), respectively. Moreover, the average TEEB and GVMP valuation of carbon sequestration in MFBR declined by 11.17% and 0.34%, respectively (Table 8).



Fig. 6 Spatial and temporal description of carbon stocks for the reference years

# Effects of environmental and disturbance factors on carbon stocks in forests

Based on the one-way ANOVA analysis, the harvesting index, elevation, slope, soil pH, total nitrogen, and phosphorus had a significant influence on carbon sequestration stock (P < 0.05) (Table 9).

Pearson correlation (r) tests exhibited both positive and negative relationships between environmental and disturbance factors with carbon stock in MFBR (Table 10). The AGC stock showed a positive relationship with SOC (r=0.10), elevation (r=0.08), TN (r=0.31), and P (r=0.11), while a significant negative relationship with the harvesting index (r = -0.21) and pH (r = -0.09).

Above-ground carbon stock showed a weak positive correlation with elevation, while based on linear mixedeffect model regression showed an increase in elevation with a decrease of AGC in MFBR. SOC showed a significant positive correlation with elevation (r=0.39) and



Fig. 7 Spatial distribution of carbon pools per pixel

TN (r=0.27), but a significant negative relationship with slope (r = -0.03), and pH (r = -0.22). Similarly, the harvesting index showed a negative relationship with slope (r = -0.09), pH (r = -0.02), TN (r = -0.31), and P (r = -0.05) and a positive correlation with elevation (r = 0.06). Soil pH showed a significant negative relationship with TN (r = -0.21), and P (r = -0.16) (Table 10).

The linear mixed regression model analysis revealed that the elevation was not significant as random effect and the variance of random effect contribution in total corbon t/ha were 3.27%. In the fixed effects analysis, only nitrogen was significant fixed effect on total carbon (conditional  $R^2$ =0.073, mariginal  $R^2$ =0.042, P<0.05)

while the other randon effects were no significant effect on total carbon t/ha. Based on the model output, nitrogen increase the total carbon t/ha by 96.79 with Intercept (389.57). The final model of nitrogen with responses is TCS = 389.5786 + 96.79 TN (Table 11).

# Discussion

### Carbon stock in carbon pools and land use/land cover

The results of this study on carbon stocks show the importance of biosphere reserves for climate change mitigation. The study has confirmed a diverse variation in LULC and carbon stock pools along the elevation gradient in MFBR. For instance, the mean carbon stock in the

LULC	1987		2002		2017		Change (19	87–2017)
	TEEB	GVMP	TEEB	GVMP	TEEB	GVMP	TEEB	GVMP
FoL	450.1	16.84	431	15.26	415.2	14.7	- 34.9	-2.14
FaL	4.4	0.06	5.36	0.07	5.87	0.08	1.47	0.02
GL	0.18	0.0087	0.16	0.007	0.17	0.008	-0.01	-0.0007
Ave	151.56	5.55	145.48	5.37	140.39	5.21	-11.17	-0.34

\*\*p<0.01

Table 8 The estimated carbon storage valuation using GVMP and TEEB in each LULC in MFBR (billion USD)

GVMP global voluntary market price, TEEB Tropical Economics of Ecosystems and Biodiversity, FoL forestland, FaL farmland, GL grassland, Ave average

**Table 9** One-way ANOVA analysis of impact factors associated with carbon storage

Impact factors	df	Mean sq	F value	P-value
H-index	1	17018.2	3350	4.25E+06***
Elevation	1	887619.7	8391	5.99E+12***
Slope	1	16976.7	3371	2.38E+09***
Soil pH	1	17020.6	3348	3.79E+05***
TN	1	15424.1	3434	6.90E+07***
Ρ	1	14216.2	3257	2.37E+04***

 Table 11
 Chi-square tests on fixed effects as response to total carbon tone per hectare

Fixed effects	Chisq	Df	Pr (> Chisq)
H. index	0.163	1	0.686
Slope	0.925	1	0.336
Soil. pH	0.928	1	0.335
TN	7.196	1	0.007**
Р	0.493	1	0.482

HI harvesting index, Slo slope, TN total nitrogen, P available phosphorus

df degree of freedom

\*\*\*P-value: - 0.001 indicates significant impact on carbon storage

LULC carbon pool increases along the elevation gradient (from site I to site IV) (Table 4). This finding is similar to the earlier finding that reported a positive relationship between elevation and carbon stock [73].

In comparison, the total carbon stock stored in forest land was higher than on grassland and farmland in MFBR (Table 4). Higher carbon stocks in forest land may be due to more vegetation cover and plant material decomposition [74]. Chuai, Huang [75] demonstrated that forest land also releases and absorbs huge amounts of carbon into and out of the atmosphere. Moreover, LULC conversion is the most important factor that causes the reduction and transformation of carbon sequestration in terrestrial ecosystems [76].

The AGC stock varied among study sites in MFBR (Table 4). The highest AGC stock was identified in study site IV (282 billion t ha<sup>-1</sup>), while the lowest (269.7 t ha<sup>-1</sup>) was in study site I of MFBR (Table 4). These results are consistent with carbon sequestration in the tropical Afromontane forest of Ethiopia (107–285) [53, 77–80] and in other tropical forests (170–271) [81–83]. This carbon stock difference may be related to DBH, height, and basal area of a tree. The variations in carbon sequestration at local, regional, and national levels

Table 10	Pearson's correlation	n coefficient	matrix for enviror	nmental and <i>i</i>	disturbance factors	(N = 8) in MFBR
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Variables	AGC	SOC	н	Ele	Slo	рН	TN	Р
AGC								
SOC	0.10 <sup>ns</sup>							
HI	-0.21*	-0.13 <sup>ns</sup>						
Ele	0.08 <sup>ns</sup>	0.39***	0.06 <sup>ns</sup>					
Slo	-0.04 <sup>ns</sup>	-0.03*	-0.09 <sup>ns</sup>	0.27***				
рН	-0.09**	-0.22**	-0.02 <sup>ns</sup>	-0.69***	-0.09**			
TN	0.31***	0.27***	-0.31**	0.10 <sup>ns</sup>	-0.12 <sup>ns</sup>	-0.21***		
Р	0.11 <sup>ns</sup>	0.14 <sup>ns</sup>	$-0.05^{ns}$	0.06 <sup>ns</sup>	-0.31*	-0.16**	0.19***	

The magnitude indicates the degree of correlation and positive signs indicate positive correlation and negative signs indicate inverse relation

ns no significance, N number of variables, MFBR Majang Forest Biosphere Reserves, AGC above ground carbon, SOC soil organic carbon, HI harvesting index, Ele elevation, Slo slope, TN total nitrogen, P available phosphorus

\*p<0.05, \*\*p<0.01, \*\*\*p<0.001

Study area	Carbon stock in different pools (t ha <sup>-1</sup> )						Source
	AGBC	BGBC	DWC	LHGC	SOC	TCS	
Anshirava forest	180.18	77.51	1.36	2.69	111.43	338.18	Fikirte et al. [92]
Awi forests	191.7	38.24	-	-	149.3	380.8	Gebeyehu et al. [53]
Bangladesh forest	96.5	14.6	-	4.2	168.1	283.4	Ullah and Al-Amin [93]
Central Africa	168.6	39.5	-	-	-	208.1	Ekoungoulou et al. [94]
Egdu forest	278.08	55.62	-	3.47	277.56	614.73	Adugna et al. [95]
Gedo forest	281	56.1	2.37	0.41	183.7	523.6	Hamere et al. [80]
Gerba Dima forest	243.8	45.9	4.64	0.03	292.1	586.7	Abyot et al. [78]
Gesha-Sayilem forest	164.5	32.9		1.27	137.67	362.4	Admassu et al. [96]
Majang Forest	272.57	54.97	3.04	0.05	176.26	506.88	Present study
Sheka Forest	176.3	44	14.7	-	233	461	Ayehu et al. [91]
Singamba forests	142.3	38.45	-	-	-	175.82	Mattia and Sesay [97]
Tara Gedam forest	306.4	61.5	-	0.9	274.3	643.1	Mohammed et al. [98]
Tulu Lafto	218.4	43.5	6.2	2.4	128.9	399.4	Fekadu et al. [99]
Upper Omo-Gibe	185	37	-	32	178	432	Abreham et al. [77]
Usambra Forest	427	85.4	418	-	-	930.4	Munishi and Shear [100]
Wujig-Waren forest	65.8	11.4	-	2.25	102.3	181.78	Negasi et al. [101]

Table 12 Comparison of carbon stock with other tropical forests studies

AGBC carbon storage in above-ground biomass, BGBC carbon storage in below-ground biomass, DWC carbon storage in dead wood biomass, LHGC carbon storage in litter, herbs, and grass biomass, SOC soil organic carbon

could be the effect of human disturbances and environmental factors in the study site of MFBR.

Similarly, the mean SOC stock (0–30 cm soil depth) was 176.26 t ha<sup>-1</sup> in MFBR. The highest SOC stock was found in study site IV (199.3 t ha<sup>-1</sup>), while the lowest was in study site I (161 t ha<sup>-1</sup>) of MFBR (Table 4). The mean SOC in MFBR was higher than earlier estimated carbon stock in other tropical forests (121–123 t ha<sup>-1</sup>) [84], a forest in Colombia (96 t ha<sup>-1</sup>) [85], Singapore (110 t ha<sup>-1</sup>) [86], the Humbo forest of Ethiopia (168 t ha<sup>-1</sup>) [87], and the Awi Zone of Ethiopia (149.2 t ha<sup>-1</sup>) [53]. Nevertheless, the mean SOC stock of MFBR was found to be lower than the SOC stock of tropical Afromontane forests (194 to 288 t ha<sup>-1</sup>) [88].

The total carbon stocks varied from 487.04 to 544.87 t ha<sup>-1</sup> in the study sites (Table 4), which is almost similar to the results quantified in the Adaba-Dodola community forest (507 t ha<sup>-1</sup>) [89], Gerba-Dima moist Afromontane forest (508.9 t ha<sup>-1</sup>) [78] in Ethiopia, and IPCC (130–510 t ha<sup>-1</sup>) [90]. Similarly, the mean total carbon stock of MFBR is higher than other findings in the Sheka Forest (461 t ha<sup>-1</sup>) [91], Humbo Forest (213.43 t ha<sup>-1</sup>) [87], and Singapore (337 t ha<sup>-1</sup>) [86]. This difference could be due to the existence of diverse tree species, elevation, human disturbance, climate, and microbial activities. Moreover, the comparison of five carbon stock pools with other tropical forests studies were showed in Table 12.

In the study sites, dominant species with higher basal areas demonstrated the highest carbon stock (Table 5) Individual plant species with higher DBH values contribute significantly to carbon sequestration in MFBR, while their extinction has a significant impact on biomass, carbon sequestration, and carbon trading. Deforestation and forest degradation also have an impact on the amount of carbon sequestered in larger trees with larger diameters [102]. The AGC and BGC in the study sites of MFBR were higher than the carbon value that was quantified by IPCC [67, 90]. This difference in AGC might be associated with the greater tree height, DBH, and basal area in MFBR.

## Effects of land use/land cover change on carbon stock

This study shows how the carbon stock pool (AGC, BGC, DWC, LHGC, and SOC) is affected by LULC change in the study period (1987–2017) (Table 6; Fig. 7). Forest land showed higher carbon stock as compared to grassland and farmland in MFBR (Table 7). Similarly, other findings indicated higher carbon stock in forest land as compared to other LULC categories [101, 103]. This significant difference in carbon stock across land cover categories could be due to the difference in tree size and trunk density per hectare. Furthermore, lower carbon stock was found in farmland that has been altered by intensive subsistence cultivation, deforestation, or anthropogenic disturbance that affected the tree, shrub, and herb growth [104].



Fig. 8 Carbon storage in MFBR over the last 30 years (1987–2017)

The InVEST carbon model results showed that the conversion of forest land and grassland into farmland leads to a reduction in carbon stock in the study area (Fig. 8). The chronological investigation indicated that the highest carbon stock was reduced in forest land among all LULC types. Carbon stock reduction was identified in all carbon pools as a result of forest land and grassland being converted into farmland in the study period (Fig. 7). This reduction is similar to phenomena in other reports [105–107]. This could be due to the expansion of settlements (urban and rural), agriculture expansion, and population pressure, which lead to deforestation and forest degradation [108, 109]. The increased urbanisation or settlement enlargement occurs at the expense of other LULC categories like farmland, forest land, and grassland [110, 111].

### Carbon storage valuation

Effective carbon stock valuation is highly relevant to the successful management of climate change impacts. It is also important for evaluating the relative advantages of climate adaptation activities and mitigation measures over time. The global voluntary market price analysis showed that the mean carbon sequestration value declined from 1987 to 2017 (Table 8). This carbon stock value reduction is linked to the change from forest cover

to other LULC types, which is consistent with other findings [77].

Similarly, according to the carbon sequestration monetary value analysis of TEEB, the mean value of carbon sequestration dropped from 1987 to 2017. The TEEB carbon sequestration value estimation is greater than that of GVMP in all study periods for MFBR (Table 8). This significant carbon value variation between GVMP and TEEB indicated a gap in carbon value estimation methods. Furthermore, using different methods of carbon pricing led to uncertainty regarding the carbon sequestration value [112]. In addition, according to the estimation of TEEB and GVMP, forest and grassland carbon sequestration values have drastically shrunk as a result of such human disturbances as deforestation. Moreover, the average TEEB and GVMP valuation of carbon sequestration in MFBR declined (Table 8).

# Effects of environmental and disturbance factors on carbon stocks in forests

The relationship between carbon and environmental and disturbance factors has become more and more important in understanding the carbon sequestration cycle. In this study, environmental and anthropogenic factors highly influence forest cover and carbon sequestration in the pools. Accordingly, the variation in carbon stock was closely related to environmental and human disturbance. Elevation, slope, and harvesting index are important environmental and disturbance factors resulting in major differences in carbon stock among study sites in MFBR (Table 10).

The harvesting index and slope were also among the environmental factors that affected the variability of carbon in the pools. Carbon stock pools increase with decreasing slope, which may be related to the moisture and soil properties of the study sites. Furthermore, tree harvesting was the primary factor responsible for the decrease in biomass and carbon stocks. This shows that clear-cutting contributes to higher carbon emissions into the atmosphere [113]. As a result, forest conservation and sustainable management help reduce carbon emissions and keep biomass and carbon in carbon pools [114, 115].

The correlation between elevation and AGC and SOC stocks were negative and positive respectively. This finding is similar to an earlier study that stated a positive relationship between elevation and SOC [116]. The positive correlation between SOC and elevation may be due to a lower temperature and increasing moisture content with increasing elevation [88, 117]. The rate of organic matter decomposition is sluggish in low temperatures, which leads to reduced microbial activities, thus assisting the increments of soil organic matter and thicker litter layer development [118]. High organic matter content in soils at higher elevations has also been reported in other Afromontane forests of Ethiopia [119, 120]. This situation leads to a reduction in  $CO_2$  release from the soil, which in turn increases soil organic carbon stocks.

Slope with AGC and SOC stocks had a negative correlation. Greater slope with decreasing soil moisture resulted in decreased vegetation cover, hence a decline in AGC and SOC stocks. Similarly, the correlation between the harvesting index with AGC and SOC stocks was negative. This indicated that the harvesting index (selective exploitation) has a significant impact on AGC and SOC stocks. Thus, illegal harvesting focused on big trees for timber production leads to a reduction of carbon stocks, which is consistent with other findings [121, 122].

## Conclusions

In this study, the results showed high carbon stocks in MFBR, which is higher than other findings in moist Afromontane forests in Ethiopia. As regards carbon pools, the mean AGC and SOC stocks were shown to be higher than other pools in MFBR. The total carbon stock and economic value for the 2017 LULC data are lower than for the 1987 LULC data. The conversion of forest land and grassland into farmland reduces the carbon stock and its economic value in MFBR. Forest cover and carbon sequestration in the pools are highly influenced by environmental and anthropogenic factors. Above-ground carbon stock showed a strong positive correlation with DBH classes (r=0.85and P=0.05), while density per hectare showed a strong negative correlation with DBH classes (r = -0.89 and P=0.05). Accordingly, the variation in carbon stock was closely related to environmental and human disturbance. Elevation, slope, and harvesting index are important environmental and disturbance factors resulting in major differences in carbon stock among the study sites in MFBR. Therefore, the gradual reduction of carbon stocks in connection with LULC change calls for urgent attention to implement successful conservation and sustainable use of forest resources in biosphere reserves.

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### Author contributions

Semegnew Tadese conceptualized, collected, analyzed, and wrote a draft manuscript. Teshome Soromessa curated data and supervised work. Abreham Berta validated data using software and reviewed the review manuscript. Tomasz Noszczyk reviewed and edited the draft manuscript. Getaneh Gebeyehu reviewed and supervised the work. Mengistie Kindu reviewed and editing manuscript.

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### Availability of data and materials

The available data can be upon request the Corresponding Author.

### Declarations

**Ethics approval and consent to participate** Not applicable.

### **Consent for publication** Not applicable.

### **Competing interests**

The authors declare that they have no competing interests.

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### References

- Sheikh AQ, et al. Terrestrial carbon sequestration as a climate change mitigation activity. J Pollut Eff Control. 2014;2:1–8.
- 2. Hunter M, et al. Tree height and tropical forest biomass estimation. Biogeosciences. 2013;10(12):8385–99.

- Lal R. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Bioscience. 2010;60(9):708–21.
- Marvin DC, et al. Amazonian landscapes and the bias in field studies of forest structure and biomass. Proc Natl Acad Sci. 2014;111(48):E5224–32.
- Kazak J, et al. Carbon sequestration in forest valuation. Real Estate Manag Valuat. 2016;24(1):76–86.
- Goodman R, Herold M. Why maintaining tropical forests is essential and urgent for a stable climate. Center for Global Development Working Paper No. 385. 2014.
- Dar JA, et al. Role of major forest biomes in climate change mitigation: an eco-biological perspective. In: Socio-economic and eco-biological dimensions in resource use and conservation. Cham: Springer; 2020. p. 483–526.
- Pan Y, et al. A large and persistent carbon sink in the world's forests. Science. 2011;333(6045):988–93.
- 9. Zachos JC, Dickens GR, Zeebe RE. An early cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature. 2008;451(7176):279–83.
- Change IC. Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press; 2007.
- 11. Speth JG, Haas PM. Global environmental governance. Chennai: Pearson Education India; 2007.
- 12. Clark B, York R. Carbon metabolism: global capitalism, climate change, and the biospheric rift. Theory Soc. 2005;34(4):391–428.
- Sabine CL, et al. Current status and past trends of the global carbon cycle. Scope-Sci Comm Probl Environ Int Council Sci Union. 2004;62:17–44.
- Pearson TR, et al. Greenhouse gas emissions from tropical forest degradation: an underestimated source. Carbon Balance Manag. 2017;12(1):1–11.
- Houghton RA. Tropical deforestation as a source of greenhouse gas emissions. In: Tropical deforestation and climate change. Washington, DC: Environmental Defense; 2005. p. 13.
- McGuire A, et al. Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO<sub>2</sub>, climate and land use effects with four process-based ecosystem models. Glob Biogeochem Cycles. 2001;15(1):183–206.
- Stephens BB, et al. Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO<sub>2</sub>. Science. 2007. https:// doi.org/10.1126/science.1137004.
- Liu YY, et al. Recent reversal in loss of global terrestrial biomass. Nat Clim Change. 2015;5(5):470–4.
- Hosonuma N, et al. An assessment of deforestation and forest degradation drivers in developing countries. Environ Res Lett. 2012;7(4): 044009.
- 20. Zheng H, et al. Realizing the values of natural capital for inclusive, sustainable development: informing China's new ecological development strategy. Proc Natl Acad Sci. 2019;116(17):8623–8.
- Sharps K, et al. Comparing strengths and weaknesses of three ecosystem services modelling tools in a diverse UK river catchment. Sci Total Environ. 2017;584:118–30.
- Seppelt R, Lautenbach S, Volk M. Identifying trade-offs between ecosystem services, land use, and biodiversity: a plea for combining scenario analysis and optimization on different spatial scales. Curr Opin Environ Sustain. 2013;5(5):458–63.
- Imran M. Geospatially mapping carbon stock for mountainous forest classes using InVEST model and Sentinel-2 data: a case of Bagrote valley in the Karakoram range. Arab J Geosci. 2021;14(9):1–12.
- 24. Nelson E, et al. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Front Ecol Environ. 2009;7(1):4–11.
- Fu Q, et al. Spatiotemporal dynamics of carbon storage in response to urbanization: a case study in the Su-Xi-Chang region, China. Processes. 2019;7(11): 836.
- Nyamari N, Cabral P. Impact of land cover changes on carbon stock trends in Kenya for spatial implementation of REDD+ policy. Appl Geogr. 2021;133:102479.

- Smith S, Braathen NA. Monetary carbon values in policy appraisal: an overview of current practice and key issues. Paris: OECD Publishing; 2015.
- Isacs L, et al. Choosing a monetary value of greenhouse gases in assessment tools: a comprehensive review. J Clean Prod. 2016;127:37–48.
- 29. Locatelli B, et al. Tropical reforestation and climate change: beyond carbon. Restor Ecol. 2015;23(4):337–43.
- Pearce D. The social cost of carbon and its policy implications. Oxf Rev Econ Policy. 2003;19(3):362–84.
- Tol RS. The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. Energy Policy. 2005;33(16):2064–74.
- 32. Brandão M, et al. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. Int J Life Cycle Assess. 2013;18(1):230–40.
- Bowen F, Wittneben B. Carbon accounting: negotiating accuracy, consistency and certainty across organisational fields. Acc Audit Acc J. 2011;24(8):1022–36.
- Ackerman F, et al. Limitations of integrated assessment models of climate change. Clim Change. 2009;95(3):297–315.
- Tallis H, Polasky S. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann N Y Acad Sci. 2009;1162(1):265–83.
- 36. Valatin G. Forests and carbon: valuation, discounting and risk management. Edinburgh: Forestry Commission; 2011.
- 37. De Groot R, et al. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst Serv. 2012;1(1):50–61.
- Van der Ploeg S, De Groot RS, Wang Y. The TEEB valuation database: overview of structure, data and results. Wageningen: Foundation for Sustainable Development; 2010.
- Negasi S, Segnon AC, Emiru B. Ecosystem service values changes in response to land-use/land-cover dynamics in dry afromontane forest in northern Ethiopia. Int J Environ Res Public Health. 2019;16(23): 4653.
- Negasi S, et al. The effects of land cover change on carbon stock dynamics in a dry afromontane forest in northern Ethiopia. Carbon Balance Manag. 2018;13(1):1–13.
- Banana AY, et al. A review of Uganda's national policies relevant to climate change adaptation and mitigation: insights from Mount Elgon. Bagor: Center for International Forestry Research; 2014.
- Choudhary CK, Fakana ST, Mengist AB. Conservation of Majang Forest Biosphere Reserve: an opportunity through community based ecotourism programme in Majang Zone, Gambella, South West Ethiopia. Asian J Conserv Biol. 2021;10(2):280–96.
- Demel T, et al. Forest resources and challenges of sustainable forest management and conservation in Ethiopia. In: Degraded forests in Eastern Africa. London: Routledge; 2010. p. 31–75.
- 44. Meron T, et al. Forest cover loss and recovery in an east African remnant forest area: understanding its context and drivers for conservation and sustainable ecosystem service provision. Appl Geogr. 2018;98:133–42.
- 45. Kefelegn G, et al. Factors controlling patterns of deforestation in moist evergreen afromontane forests of Southwest Ethiopia. For Ecol Manag. 2013;304:171–81.
- Tadese S, et al. Woody species composition, vegetation structure, and regeneration status of Majang forest biosphere reserves in Southwestern Ethiopia. Int J For Res. 2021. https://doi.org/10.1155/2021/5534930.
- 47. Kent M. Vegetation description and data analysis: a practical approach Wiley. Chichester: Blackwell; 2012.
- Chave J, et al. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia. 2005;145(1):87–99.
- Pearson TR. Measurement guidelines for the sequestration of forest carbon, vol. 18. Newtown Square: US Department of Agriculture, Forest Service, Northern Research Station; 2007.
- MacDicken KG. A guide to monitoring carbon storage in forestry and agroforestry projects. Arlington: Winrock International Institute for Agricultural Development; 1997.
- 51. Pearson T, Walker S, Brown S. Sourcebook for land use, land-use change and forestry projects. Washington, DC: World Bank; 2005. p. 29.
- 52. Dick RP, Thomas DR, Halvorson JJ. Standardized methods, sampling, and sample pretreatment. In: Methods for assessing soil quality, vol. 49. New York: Wiley; 1997. p. 107–21.

- Gebeyehu G, et al. Carbon stocks and factors affecting their storage in dry afromontane forests of Awi Zone, northwestern Ethiopia. J Ecol Environ. 2019;43(1):1–18.
- Sagar R, Raghubanshi A, Singh J. Tree species composition, dispersion and diversity along a disturbance gradient in a dry tropical forest region of India. For Ecol Manag. 2003;186(1–3):61–71.
- 55. Tadese S, Soromessa T, Bekele T. Analysis of the current and future prediction of land use/land cover change using remote sensing and the CA-Markov model in Majang forest biosphere reserves of Gambella, southwestern Ethiopia. Sci World J. 2021. https://doi.org/10.1155/2021/ 6685045.
- Bagstad KJ, et al. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosyst Serv. 2013;5:27–39.
- Guerry AD, et al. Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning. Int J Biodivers Sci Ecosyst Serv Manag. 2012;8(1–2):107–21.
- Bouyoucos GJ. Hydrometer method improved for making particle size analyses of soils 1. Agron J. 1962;54(5):464–5.
- Sparks DL, et al. Methods of soil analysis, part 3: chemical methods, vol. 14. New York: Wiley; 2020.
- 60. Bremner JM. Nitrogen-total methods of soil analysis: part 3 chemical methods, vol. 5. New York: Wiley; 1996. p. 1085–121.
- Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37(1):29–38.
- 62. Bray RH, Kurtz LT. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 1945;59(1):39–46.
- 63. Team RC. R: a language and environment for statistical computing. Vienna: R foundation for statistical computing. 2017
- Chave J, et al. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Change Biol. 2014;20(10):3177–90.
- 65. Zanne AE, et al. Global wood density database. 2009.
- Réjou-Méchain M, et al. Biomass: an R package for estimating aboveground biomass and its uncertainty in tropical forests. Methods Ecol Evol. 2017;8(9):1163–7.
- Hiraishi T, et al. 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands. Switzerland: IPCC; 2014.
- Niquisse S, et al. Ecosystem services and biodiversity trends in Mozambique as a consequence of land cover change. Int J Biodivers Sci Ecosyst Serv Manag. 2017;13(1):297–311.
- Brown DR, et al. Poverty alleviation and environmental restoration using the clean development mechanism: a case study from Humbo, Ethiopia. Environ Manag. 2011;48(2):322–33.
- Kemerink-Seyoum J, et al. Sharing benefits or fueling conflicts? The elusive quest for organizational blue-prints in climate financed forestry projects in Ethiopia. Glob Environ Change. 2018;53:265–72.
- McVittie A, Hussain S. The economics of ecosystems and biodiversityvaluation database manual. Edinburgh: Sustainable Ecosystems Team at the Scotland's Rural College; 2013.
- 72. Temesgen G, et al. Estimating the impacts of land use/land cover changes on ecosystem service values: the case of the Andassa watershed in the Upper Blue Nile basin of Ethiopia. Ecosyst Serv. 2018;31:219–28.
- Sharma CM, et al. Tree diversity and carbon stocks of some major forest types of Garhwal Himalaya, India. For Ecol Manag. 2010;260(12):2170–9.
- Wójcik-Leń J, Leń PL. Proposed algorithm for the identification of rural areas with regard to variability of soil quality. Comput Electron Agric. 2021;188: 106318.
- 75. Chuai X, et al. Land use structure optimization based on carbon storage in several regional terrestrial ecosystems across China. Environ Sci Policy. 2013;25:50–61.
- Zhang M, et al. Impact of land use type conversion on carbon storage in terrestrial ecosystems of China: a spatial-temporal perspective. Sci Rep. 2015;5(1):1–13.
- 77. Abreham BA, et al. Expressing carbon storage in economic terms: the case of the upper Omo Gibe Basin in Ethiopia. Sci Total Environ. 2022;808: 152166.

- Abyot D, Teshome S, Bikila W. Carbon stock of the various carbon pools in Gerba-Dima moist Afromontane forest, south-western Ethiopia. Carbon Balance Manag. 2019;14(1):1–10.
- Yelemfrhat ST, Teshome S. Carbon stock variations along altitudinal and slope gradient in the forest belt of Simen Mountains National Park, Ethiopia. Am J Environ Prot. 2015;4:199–201.
- Hamere Y, Teshome S, Mekuria A. Carbon stock analysis along altitudinal gradient in gedo forest: implications for forest management and climate change mitigation. Am J Environ Prot. 2015;4(5):237–44.
- Tanner LH, et al. Biomass and soil carbon stocks in wet montane forest, Monteverde Region, Costa Rica: assessments and challenges for quantifying accumulation rates. Int J For Res. 2016. https://doi.org/10.1155/ 2016/5812043.
- Spracklen D, Righelato R. Tropical montane forests are a larger than expected global carbon store. Biogeosciences. 2014;11(10):2741–54.
- 83. Willcock S, et al. Quantifying and understanding carbon storage and sequestration within the Eastern Arc mountains of Tanzania, a tropical biodiversity hotspot. Carbon Balance Manag. 2014;9(1):1–17.
- Lal R. Soil carbon sequestration to mitigate climate change. Geoderma. 2004;123(1–2):1–22.
- 85. Sierra CA, et al. Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. For Ecol Manag. 2007;243(2–3):299–309.
- 86. Ngo KM, et al. Carbon stocks in primary and secondary tropical forests in Singapore. For Ecol Manag. 2013;296:81–9.
- Alefu C, Teshome S, Eyale B. Carbon stock in woody plants of Humbo forest and its variation along altitudinal gradients: the case of Humbo district, Wolaita Zone, southern Ethiopia. Int J Environ Prot Policy. 2015;3(4):97–103.
- Selmants PC, et al. Ecosystem carbon storage does not vary with mean annual temperature in Hawaiian tropical montane wet forests. Glob Change Biol. 2014;20(9):2927–37.
- Nega MB, Teshome S, Eyale B. Above-and below-ground reserved carbon in Danaba community forest of Oromia region, Ethiopia: implications for CO<sub>2</sub> emission balance. Am J Environ Prot. 2015;4(2):75–82.
- 90. Penman J, et al. Good practice guidance for land use, land-use change and forestry. 2003.
- Ayehu F, Teshome S, Bikila W. Carbon sequestration and storage value of coffee forest in Southwestern Ethiopia. Carbon Manag. 2021;12(5):531–48.
- Fikirte A, et al. Effects of Environmental Factors on Carbon Stocks of Dry Evergreen Afromontane Forests of the Choke Mountain Ecosystem, Northwestern Ethiopia. Int J For Res. 2022.
- Ullah M, Al-Amin M. Above-and below-ground carbon stock estimation in a natural forest of Bangladesh. J For Sci. 2012;58:372–9.
- 94. Ekoungoulou RS, et al. Evaluating the carbon stock in above-and below-ground biomass in a moist central African forest. Appl Ecol Environ Sci. 2015;3:51–9.
- Adugna F, Teshome S, Mekuria A. Forest carbon stocks and variations along altitudinal gradients in Egdu forest: implications of managing forests for climate change mitigation. Sci Technol Arts Res J. 2013;2:40–6.
- 96. Admassu A, et al. Carbon stock of the moist Afromontane forest in Gesha and Sayilem Districts in Kaffa Zone: An implication for climate change mitigation. J Ecosyst Ecograph. 2019;9:1–8.
- 97. Mattia SB, Sesay S, Ground Forest Inventory and Assessment of Carbon Stocks in Sierra Leone, West Africa. Nat Res Manag Biolog Sci. 2020.
- Mohammed G, Teshome S, Satishkumar B. Forest carbon stocks in woody plants of Tara Gedam forest: Implication for climate change mitigation. Sci Technol Arts Res J. 2014;3:101–7.
- Fekadu G, et al. Carbon Stock Density of the Different Carbon Pools in Tulu Lafto Forest and Woodland Complex: Horo Guduru Wollega Zone, Oromia Region, Ethiopia. Eur J Biophys. 2021;9:37–47.
- Munishi P, Shear T. Carbon storage in Afromontane rain forests of the Eastern Arc mountains of Tanzania: their net contribution to atmospheric carbon. J Trop For Sci. 2004;78–93.
- Negasi S, et al. Carbon stocks and sequestration potential of dry forests under community management in Tigray, Ethiopia. Ecol Process. 2017;6(1):1–11.
- 102. Gibbs HK, et al. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environ Res Lett. 2007;2(4): 045023.

- Rajput BS, Bhardwaj D, Pala NA. Factors influencing biomass and carbon storage potential of different land use systems along an elevational gradient in temperate northwestern Himalaya. Agrofor Syst. 2017;91(3):479–86.
- Tessema T, Kibebew K. Carbon stock under major land use/land cover types of Hades sub-watershed, eastern Ethiopia. Carbon Balance Manag. 2019;14(1):1–14.
- Singh SL, et al. Effect of land use changes on carbon stock dynamics in major land use sectors of Mizoram, Northeast India. J Environ Prot. 2018;9(12):1262.
- 106. Qu R, et al. A study of carbon stock changes in the Alpine Grassland Ecosystem of Zoigê, China, 2000–2020. Land. 2022;11(8): 1232.
- Ramesh T, et al. Soil organic carbon dynamics: impact of land use changes and management practices: a review. Adv Agron. 2019;156:1–107.
- Solomon MM. Effect of land use land cover changes on the forest resources of Ethiopia. Int J Nat Resour Ecol Manag. 2016;1(2):51.
- 109. Fornal-Pieniak B, et al. Where is the forest core area? Gradients of flora in the ecotone of urban forests in Warsaw. Landsc Urban Plan. 2022;224:104427.
- 110. Price B, et al. Future landscapes of Switzerland: risk areas for urbanisation and land abandonment. Appl Geogr. 2015;57:32–41.
- 111. Prus B, Dudzińska M, Bacior S. Determining and quantifying the historical traces of spatial land arrangements in rural landscapes of Central and Eastern Europe. Sci Rep. 2021;11(1):23421.
- Canu DM, et al. Estimating the value of carbon sequestration ecosystem services in the Mediterranean Sea: an ecological economics approach. Glob Environ Change. 2015;32:87–95.
- 113. Huang M, Asner GP. Long-term carbon loss and recovery following selective logging in Amazon forests. Glob Biogeochem Cycles. 2010. https://doi.org/10.1029/2009GB003727.
- 114. Sasaki N, et al. Sustainable management of tropical forests can reduce carbon emissions and stabilize timber production. Front Environ Sci. 2016;4: 50.
- 115. Zięba-Kulawik K, et al. Improving methods to calculate the loss of ecosystem services provided by urban trees using LiDAR and aerial orthophotos. Urban For Urban Green. 2021;63:127195.
- Khadanga SS, Jayakumar S. Tree biomass and carbon stock: understanding the role of species richness, elevation, and disturbance. Trop Ecol. 2020;61(1):128–41.
- 117. Hoffmann U, et al. Assessment of variability and uncertainty of soil organic carbon in a mountainous boreal forest (Canadian Rocky Mountains, Alberta). CATENA. 2014;113:107–21.
- Walz J, et al. Regulation of soil organic matter decomposition in permafrost-affected Siberian tundra soils-impact of oxygen availability, freezing and thawing, temperature, and labile organic matter. Soil Biol Biochem. 2017;110:34–43.
- Schindlbacher A, et al. Temperature sensitivity of forest soil organic matter decomposition along two elevation gradients. J Geophys Res Biogeosci. 2010. https://doi.org/10.1029/2009JG001191.
- 120. Tamrat B. Phytosociology and ecology of a humid afromontane forest on the central plateau of Ethiopia. J Veg Sci. 1994;5(1):87–98.
- 121. Sasaki N, Chheng K, Ty S. Managing production forests for timber production and carbon emission reductions under the REDD+ scheme. Environ Sci Policy. 2012;23:35–44.
- 122. Lindsell JA, Klop E. Spatial and temporal variation of carbon stocks in a lowland tropical forest in West Africa. For Ecol Manag. 2013;289:10–7.

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