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CARBON STORAGE OF SELECTED CHURCH FORESTS IN NORTHERN ETHIOPIA: IMPLICATIONS FOR CLIMATE CHANGE MITIGATION

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ABSTRACT: *Forests are known to play an important role in regulating the global climate, by serving as a natural sink of CO_2 to mitigate climate change. Churches and monasteries have a long history of planting, protecting and conserving trees. This study on selected Church forests aimed to estimate the carbon stock and its variation along altitudinal gradients. Primary data collection was carried out through by field inventory and secondary data were obtained from different sources. To collect vegetation data, particularly above Ground Biomass (AGB), comprising 64 plots, with a size of 20 m x 20 m at an interval of 100 m, were laid along established transects 200 m apart. For litter and soil sample collection, five sub quadrats of 1 m x 1 m were established at the four corners and center of every sub quadrat. A composite method was also used for litter and soil sampling. Data analysis of various carbon pools measured in the forests were analyzed on Excel data sheet and R software. The results revealed that the total mean carbon stock density of Church forests was 133.14 t/ha, aboveground biomass carbon was 24.73 t/ha, belowground biomass carbon was 6.41t/ha, litter biomass carbon was 1.80 t/ha and soil carbon stock was 100.19 t/ha. Furthermore, the results of this study showed that altitude has no significant impact on carbon pools. Overall, this study may enlighten our knowledge of the carbon stock of the study site and contribute to Church forests playing a role in climate change mitigation.*

KEYWORDS: altitude; allometric equation; carbon stock; church forest; climate change; forests

INTRODUCTION

Nature provides goods and services that improve the quality of life and well-being of human beings (Díaz *et al.*, 2018). However, the effective functioning of these services is compromised when ecosystems are under pressure from habitat change, land use change, overexploitation, invasive alien species, pollution and climate change (Carvalho *et al.*, 2014; Lipton *et al.*, 2018). Climate change is the single largest environmental crisis facing Earth, which may lead to unfathomable humanitarian disasters (Mal *et al.*, 2018). According to the current scientific consensus, warming of the global climate system seems to be unambiguous and is most likely due to anthropogenic emissions of Greenhouse Gases (GHG) particularly Carbon dioxide (CO_2) (IPCC, 2014). It has been estimated that global release of CO_2 has increased by 2.2% from 2000 to 2010 (IPCC, 2014).

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keeping the temperature increase below 2°C, compared to the pre industrial levels requires a reduction in CO_2 and other GHG emissions.

For this purpose, the intergovernmental panel on climate change (IPCC) emphasizes an integrated strategy for climate change mitigation that involves reducing the use of fossil 3 energy and fossil-based materials, and enhancing carbon sinks in the land use, land use change, and forestry (LULUCF) sector (IPCC 2014a, 2014b). Thus, the forest sector is considered one of the main options in many climate change mitigation policies to combat human-induced carbon emissions (Reyer et al., 2009).

Forests offer possible pathways for climate change mitigation through the sequestration and storage of carbon in forests and harvested biomass, and the use of harvested biomass as a substitute for fossil energy and fossil-based materials to reduce atmospheric CO_2 emissions (Kurz et al. 2016). According to the IPCC (2007a) report, until 2050 on average, forests have a biophysical mitigation potential of 5,380 Mt CO2/yr.

Strategically, the role of tropical forests in the global carbon cycle and its potential to reduce carbon dioxide emissions by photosynthesis have made it crucial to estimate the carbon stock of forests (IPCC, 2006), as they are prominent for their highest carbon density and largest area coverage compared to other ecoregions of the world. They serve as a buffer to the effects of climate change (Aryal et al., 2014).

Sacred Natural Sites (SNS) are portions of land or water that hold spiritual significance for specific communities (Wild *et al.*, 2008). They are often hotspots of cultural as well as biological diversity (Verschuuren *et al*., 2010). These include sites that have been physically altered by those who hold them to be sacred due to burial grounds or constructions of monuments which are known as semi natural sacred sites, or those that have been less actively altered, such as areas that are preserved and set aside due to their spiritual significance (Anthwal *et al*., 2010).

According to Wild *et al.*, (2010) SNSs are nodes of resilience, restoration, and adaptation to climate change. These sites offer opportunities for building landscape connectivity networks and recovering ecologically sound, because they form important refuges for biodiversity and maintain a dynamic cultural fabric in the face of global change.

There are many SNSs around the world, that are as diverse as the countries and cultures that they represent (Finlay and Palmer, 2003). As a result, these groves are represented globally with different names and functions, such as Church forests, Fetish forests, and sacred forests (Cardelús *et al.*, 2012). They are found in many parts of the world, including Japan, Morocco, India, Ghana, and Ethiopia (Cardelús *et al*., 2013).

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In northern Ethiopia, forests around churches are the last remnant forest patches surrounded by highly depleted bare grounds, and are currently under the threat of encroachment due to farmland expansion and extensive grazing (Wassie and Lowman, 2014). The forests are also called sacred groves and have been kept for the past many hundred years through the strong biblical basis, theological thoughts, religious belief and commitment of the communities (Wassie, 2002). The churches and monasteries of the Ethiopian Orthodox Tewahido church (EOTC) are often surrounded by small natural forest characterized by a high floral and faunal diversity with many indigenous and rare species (Wassie, 2007; Cardelús *et al.*, 2013), as the Church has a long history of protecting trees around churches.

In Ethiopia the bulk of research on Church forests centers on ecological and forest cover conditions (Scull et al., 2017; Cardelús et al., 2013; Aerts et al., 2016). Thus, understanding their carbon stock and role in climate change mitigation is scarce even though some research has been done thus far. Therefore, this study aimed to estimate the carbon stock (storage) of these Church forests by surveying of forest stand measurements, and by quantifying the carbon stock in above and below ground biomass, dead litter and soil organic carbon, which are known potential pools for carbon sinks. The results of this study will be useful in planning and implementing forest restoration management and knowledge-based conservation strategies at the community, regional or national level.

MATERIALS AND METHODS

Study Areas

The study was carried out in four Church forests, namely those of (1) Abune Aregawi Debere Bereket Church, (2) Montogera Estifanos Church Forest in Amhara Regional State (3) Mai-Anbesa Kidane Miheret Monastery, and (4) Emba Kidest Arsema Mekane Kidusan Andinet Monastery Forest in Tigray Regional State, as the geographical context within which the research questions were explored. Each of the Church forests is described separately as follows.

Abune Aregawi Debere Bereket Church Forest

Geographical location

Abune Aregawi Debere Bereket Church Forest is found in the South Gondar Zone of the Amhara Region (Figure 1), particularly in the Fogera district with an area of 21.8 ha. It is located at 37°49'E to 37° 98'E longitude and 11° 67'N to 12°04' N latitude. The altitude of Fogera district ranges from 1783 to 2410 m.a.s.l. (meter above sea level). Woreta is the capital of the district and is found 625 km from Addis Ababa and 55 km from the regional capital, Bahir Dar. The district is bordered to the north by Limo Kemekem; Dera to the south; Lake Tana to the west, and Farta to the east.

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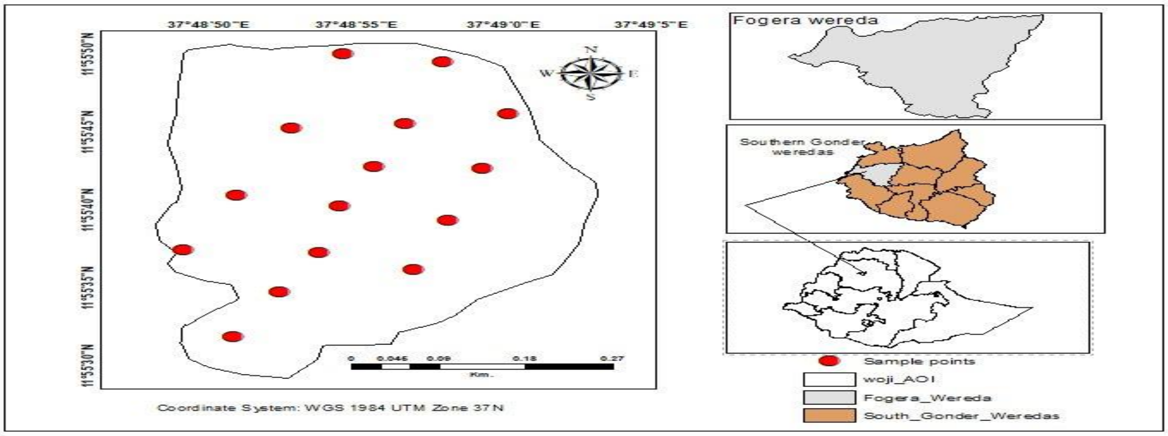

Figure 1. The location of the study site (Abune Aregawi Debere Bereket Church Forest) in Ethiopia.

Climate

Meteorological data from 1986 to 2019 obtained from the Ethiopian National Meteorology Agency (ENMA) of the nearest station (Wereta) were extracted, analyzed and presented (Figure 2). The average annual rainfall is 1454 mm, while the annual mean temperature also varies from 10.6°C to 30.3°C. Rain fall is monomodal.

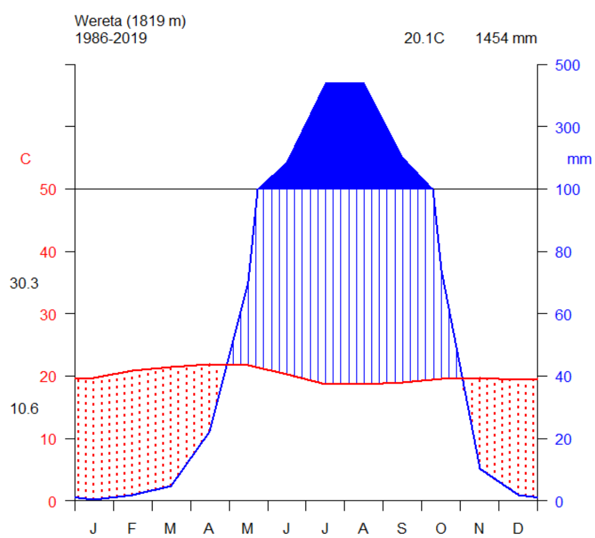

Figure 2. Climate diagram of the nearest station (Abune Aregawi Debere Bereket Church Forest) (Data source: ENMA)

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Topography, soil and land use

Agro-ecologically, the district is classified as ‘weina dega’ (mid-land). As the district Agricultural Office indicated, the soil type of the district is categorized as 65% black soil (vertisol), 20% brown soil, 12% red soil, and 3% gray soil.

The land use/cover of Fogera district is dominated by agricultural land; 69.9% of the total land mass within woreda is allocated to agriculture, 14.59% to grazing land, and 4.67 % to forest land. (Secondary information from District Agricultural Office).

Montogera Estifanos Church Forest

Geographical location

Montogera Estifanos Church Forest is found in the Amhara Regional State, with an area of 7.5 ha. The LiboKemkem district is one of the districts located in south Gondar in the northwest part of Ethiopia. The town of the district is located 645 kilometers from Addis Ababa to the north and 85 kilometers from the regional city of Bahir Dar to the north. It is located at 37°57'E to 37° 96'E longitude and 11° 96'N to 12°36'N latitude. The district is bordered in the north, by Semien Gondar Zone; in the south; by Fogera district; in the west, by Lake Tana; and in the east; by Belesa Woreda. The elevation of the district ranges from 1783 to 2410 m.a.s.l.

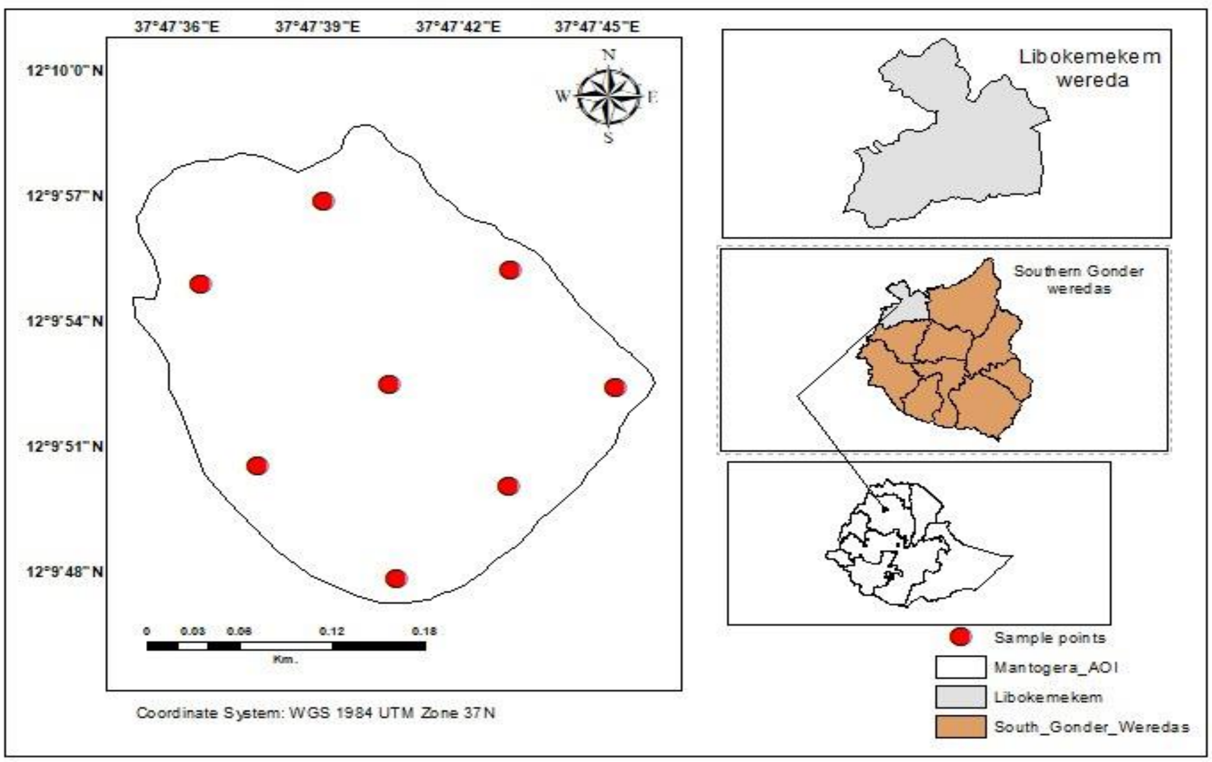

Figure 3. The location of the study site (Montogera Estifanos Church Forest) in Ethiopia.

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Climate

Meteorological data from 1986 to 2019 obtained from ENMA of the nearest station (Addis Zemen) were extracted, analyzed, and presented (Figure 4). The study area has a mean annual rainfall of 1347 mm. The mean annual temperature of the study area ranges from 8.7 to 32°C.

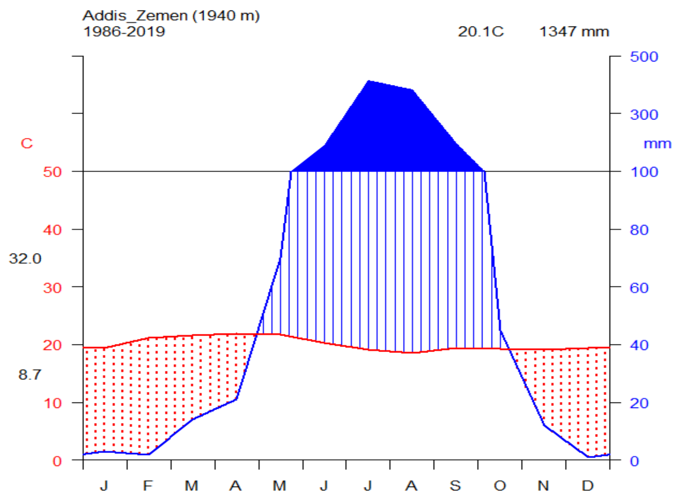

Figure 4. Climate diagram of the nearest station (Montogera Estifanos Church Forest)

Topography, soil and land use

The agro climatic zone of the district consists of 81.1% Woinadega, and 18% Dega, and 0.9 of kolla. LiboKemkem is characterized by plain, mountainous, ups and downs, depression and swampy areas, which account for 42%, 21%, 30%, 1% and 6%, respectively. The soils of the study area were categorized as 60% brown soil, 22% red soil, 15% black soil, and 3% gray soil. A survey of the land in this district shows that 39.9% of the total land mass within the district is allocated to agriculture. grazing land, 14.3%; forest land 4.6 %, and others 41.5% (secondary information from district Agricultural Office).

Mai- Anbesa Kidane Miheret Monastery Fores

Geographical location

Mai-Anbesa Kidane Miheret Monastery Forest is found in Enderta, a district found in the southeastern Administrative Zone of the Tigray Regional State in Ethiopia with an area of 33 ha. Geographically it lies from 13º 24' to 13º 64' North Latitude and 39º 27' to 39º 74' Eastern Longitude, and the altitude in the area ranges from 1400 m to 1800 m. It shares borders with Wukro to the north; Degua Temben to the west; the afar region to the east, and Hintalo Wajirat to the south.

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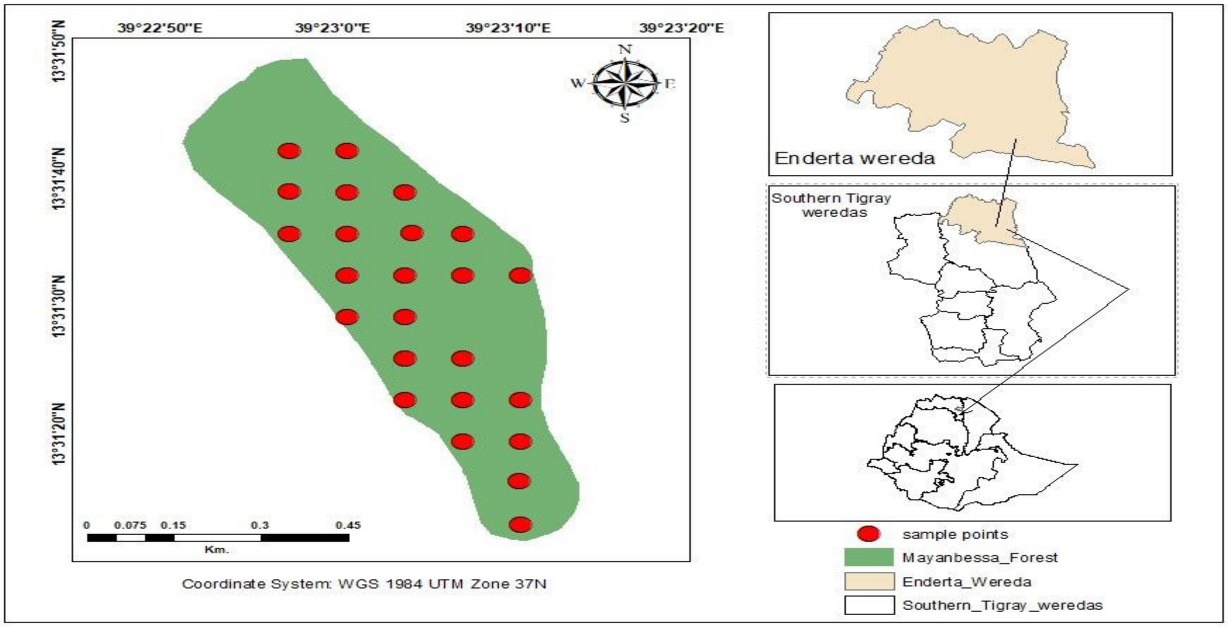

Figure 5. The location of the study site (Mai- Anbesa Kidane Miheret Monastery Forest) in Ethiopia**.**

Climate

Meteorological data from 1987 to 2019 obtained from ENMA of the nearest station (Mekele airport) were extracted, analyzed, and presented (Figure 6). It is also characterized by rainfall of 575 mm per annum, and the minimum and maximum temperatures are 8.9°C and 27°C, respectively.

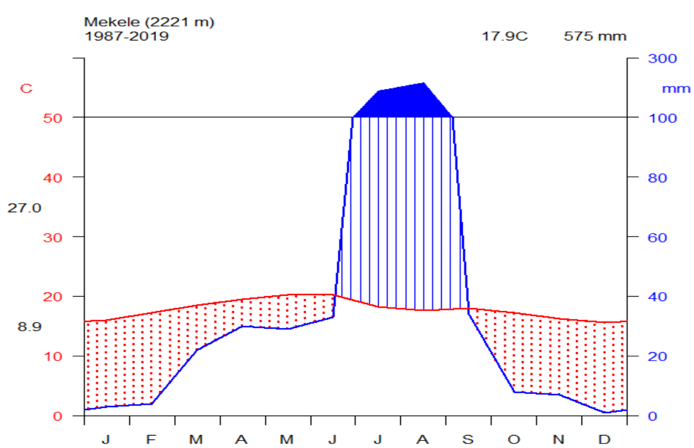

Figure 6. Climate diagram of the nearest station (Mai- Anbesa Kidane Miheret Monastery Forest) (Data source: ENMA)

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Topography, soil and land use

A greater portion of the agroecology of Enderta lies in the Midland agro-ecological zone. The landscape is mostly plains and hills, with bush vegetation. Its soil type is dark reddish-brown and dark black clays and other types.

Emba Kidest Arsema Mekane Kidusan Andinet Monastery Forest

Geographical location

Emba Kidest Arsema Mekane Kidusan Andinet Monastery Forest is found in Hintalo Wajirat district in the southeastern zone of Tigray, with an area of 16.9 ha. It is located 745 km north of the capital Addis Ababa, and 38 km south of Mekelle, the capital of the Tigray Region. Geographically, it is positioned between 39°27' to 39°81' E (Latitude) and 12°88' to 13°41' N (Longitude), and the altitude of the district ranges from 1550 to 3400 meters above sea level. It is bordered by Enderta woreda to the north; Raya Azebo district to the south; Afar region to the east, and Endamehoni and Alaje district to the west.

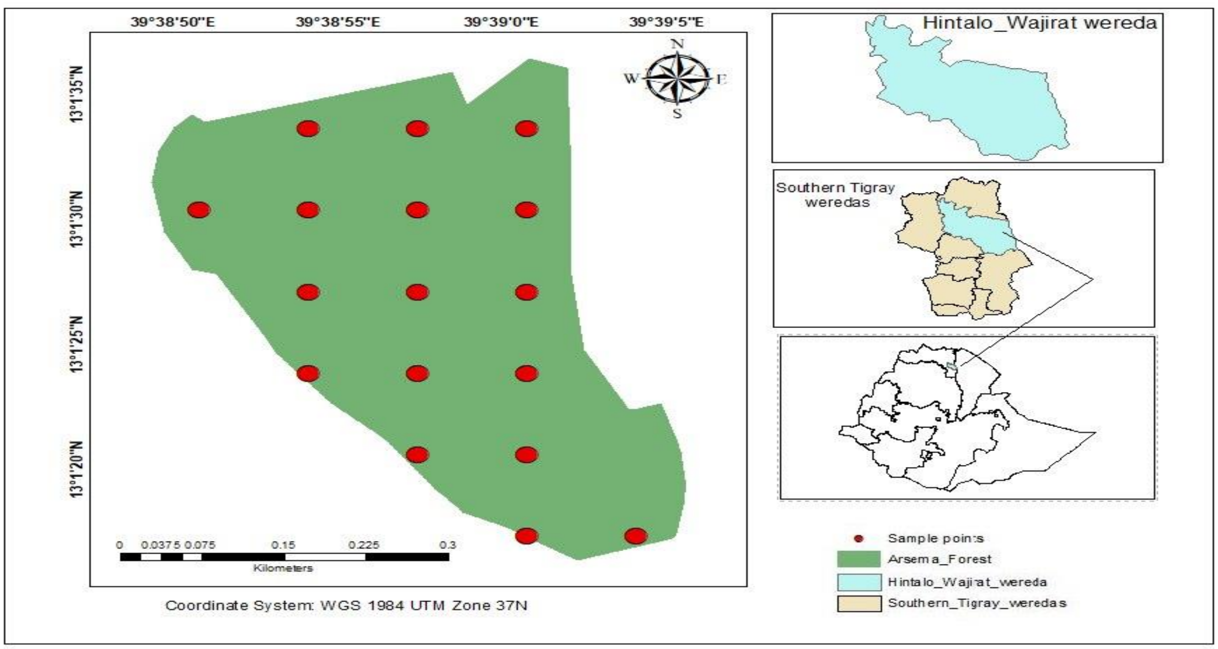

Figure 7. The location of the study site (Emba Kidest Arsema Mekane Kidusan Andinet Monastery Forest) in Ethiopia.

Climate

Meteorological data from 2005 to 2020 obtained from ENMA of the nearest station (Hewane) were extracted, analyzed, and presented (Figure 8). The study area has mean annual rainfall which ranges from 184 mm, and the mean annual temperature estimate ranges from 7.3 to 29.5°C.

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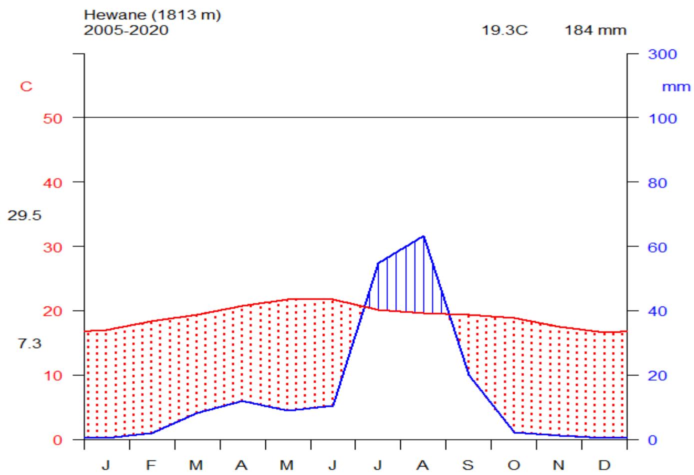

Figure 8. Climate diagram of the nearest station (Emba Kidest Arsema Mekane Kidusan Andinet Monastery Forest) (Data source: ENMA).

Topography, soil and land use

The agroecology of the district is Kolla (22.5%), Weina-Dega (63.75%), and Dega (13.75%). In Hintalo-Wajirat the soil compositions are vertisols, cambisols and fluvisols. The central part of the district is mostly characterized by black soil with a cracking nature dominated by clay particles (Relief society of Tigray, 2000 in Mohammed, 2006).

METHODOLOGY

Sampling design

At each study site, sampling plots measuring 20 m ×20 were demarcated along a 100m transect; using a measuring tape and GPS. The boundaries of the main plots were marked, and altitude, latitude and longitude data were recorded from the center of each main plot. Inside the quadrats, five 1 m × 1 m subsampling units (four at the corners and one center of the main plot) were located for fallen litter and soil sampling.

Methods of data collection

Inventory of trees

To estimate the carbon stock of each study site, trees having diameter at Breast Height (DBH) equal to or greater than 5 cm were used to estimate the carbon stock of each study site, since in carbon stock measurements the minimum diameter is often 5 cm DBH, as recommended by IPCC (2006) and (Pearson et al., 2007).

All trees with DBHs greater than or equal to 5 cm and heights of 1.3m were measured by using a diameter tape and hypsometer. In cases where trees branched at or below breast height, diameter

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was measured separately for each branch and within the quadrat.The diameter at each stem was measured separately for trees with multiple stems connecting near the ground. A tree with multiple stems at 1.3 m height was treated as a single individual.

Litter sampling

Litter samples were collected from 1 m × 1 m quadrat subplots in each plot. All the litter within 1 m^2 quadrat subplots of each main plot was collected, weighed, recorded, placed in a plastic bag, and labeled to which sample plot it belonged. Then, the field wet weight was recorded and taken to the laboratory to determine the litter biomass. Oven- dried samples were taken in preweighed crucibles. The samples were ignited at 550°C for one hour in a muffle furnace. After cooling, the crucibles with ash were weighed, and the percentage of organic carbon was calculated. Finally, the carbon in leaf litter t ha^{-1} for each site was determined.

Soil sampling

The soil samples for soil carbon determination were collected from sample plots laid out for litter sampling. In each sub quadrat one composite soil sample was taken using a core sampler auger, at a depth of 30 cm from the four corners and center of the plots. The bulk density (BD) of the soil samples was collected by using a core sampler. Soil organic carbon was determined in the laboratory following the Walkley-Black method (1934). In the laboratory, soil samples were dried at 105°C for 24 hours to remove soil moisture and to determine the percentage of organic carbon as well as the bulk density (Pearson *et al.*, 2005). The soil organic carbon was calculated according to Pearson *et al* (2005).

Carbon stock estimation

Above Ground Biomass (AGB) carbon stock estimation

To estimate the AGB carbon, the total height and perimeter at breast height of all living stems ≥5 cm DBH within each plot were measured and identified to the species level. Then, the above ground biomass (AGB) was estimated using allometric equations.
The generic allometric equations developed by Chave *et al*., (2014) were considered a suitable equation to estimate aboveground biomass in a tropical forest. Since this model performed well across forest type and bioclimatic conditions of pantropical areas, this study used the model below to determine the AGB (Chave *et al*., 2014);-.
$AGB = 0.0673 *(WD * DBH^2 * H) ^\wedge 0.976$ -------------------------------------- *(equ.1).*
where: AGB = aboveground biomass (in kg dry matter), WD = wood density (g/cm3), DBH = diameter at breast height (in cm), and H = total height of the tree (in m).
Accordingly, the carbon content of tree vegetation in the study area was estimated by following IPCC (2006) which recommended the use of 47% (conversion factor: 0.47) for estimations of carbon concentration for aboveground biomass of tropical and subtropical forests.
$C = 0.47* AGB$. ………………………………………………………….. *(equ.2).*

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Below Ground Biomass (BGB) carbon stock estimation

To estimate the carbon stock of belowground biomass, the methodology proposed by IPCC (2006), that is, the application of a root- to- shoot ratio method, was used.

The equation used to calculate the belowground biomass is given below:

BGB = AGB* 0.26 -- *(equ.3).*

where BGB is belowground biomass, AGB is aboveground biomass, and 0.26 is the conversion factor (or 26% of AGB). The biomass stock density was converted to carbon stock density by multiplying the default value of the 0.47 carbon fraction (IPCC, 2006).

C = 0.47* BGB. ……………………………………………………….. *(equ.4).*

Estimation of Carbon in the Litter Biomass (LB)

According to Pearson *et al.* (2005), the estimation of the amount of biomass in leaf litter can be calculated by:

$$LB = \frac{Wfield}{A} * \frac{Wsub\_sample(dry)}{Wsub\_sample(fresh)} * \frac{1}{10{,}000} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (equ.5)$$

where: LB = litter (biomass of litter t ha^{-1})

W_{field} = weight of wet field sample of litter sampled within an area of size 1 m^2 (g);

A = size of the area in which litter was collected (ha);

W subsample, dry = weight of the oven dried subsample of litter taken to the laboratory to determine moisture content (g); and

W subsample, fresh = weight of the fresh subsample of litter taken to the laboratory to determine moisture content (g).

The percentage of organic carbon storage from the dry ash in the litter carbon pool was calculated as follows (Allen *et al.*, 1986)

%Ash = $wc{-}wa/\ wb{-}wa * 100$ …………………………………………. *(equ.6)*

$\%C = (100 - Ash\ \%) * 0.58$ ……………………………………………… *(equ.7)*

This is by considering 58% carbon in ash-free soil material.

where, C = organic carbon (%); Wa = the weight of the crucible (g); Wb = the weight of oven-dried grind samples and crucibles (g), and Wc = the weight of ash and crucibles (g). Finally, the carbon in litter t/ha for each sample was determined.

Carbon stocks in dead litter biomass

CL = LB × % C……………………………… *(equ.8)*

where CL is the total carbon stock in the dead litter in t ha^{-1}; and % C is the carbon fraction determined in the laboratory (Pearson *et al.,* 2005).

Estimation of Soil Organic Carbon

The carbon stock density of soil organic carbon was calculated as recommended by Pearson *et al.* (2005) from the volume and bulk density of the soil.

V = h × π r^2 **………………………………………** *(equ.9)*

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where V is the volume of the soil in the core sampler augur in cm^3, h is the height of the core sampler augur in cm, and r is the radius of the core sampler augur in cm (Pearson *et al.*, 2005). Moreover, the bulk density of a soil sample can be calculated as follows:

$BD = \frac{Wav,\ dry}{V}$ …………………………………… *(equ.10)*

where BD is the bulk density of the soil sample per, $W_{av,\ dry}$ is the average air-dry weight of the soil sample per quadrant, and V is the volume of the soil sample in the core sampler auger in cm^3 (Pearson *et al.*, 2005).

SOC = BD * d * % C …………………………………… *(equ.11)*

where, SOC= soil organic carbon stock per unit area (t ha^{-1}),
BD = soil bulk density (g cm^{-3}),
D = the total depth at which the sample was taken (30 cm), and
%C = Carbon concentration (%)

Total Carbon Stock Density

The total carbon stock density of each site was calculated by adding the carbon stock densities of the individual carbon pools using the formula (Pearson *et al.*, 2005).

Carbon stock density of a study area:

$C_{density} = C_{AGB} + C_{BGB} + C_{Lit} + SOC$……………………… *(equ.12)*

where: $C_{density}$ = Carbon stock density for all pools [ton ha^{-1}]
C_{AGTB} = Carbon in above -ground tree biomass [t C ha^{-1}]
C_{BGB} = Carbon in below-ground biomass [t C ha^{-1}]
C_{Lit} = Carbon in dead litter [t C ha^{-1}]
SOC = Soil organic carbon

The total carbon stock was then converted to tons of CO_2 equivalent by multiplying it by 44/12, or 3.67 (Pearson *et al.*, 2007).

Statistical analysis

The mean values of soil organic carbon, litter carbon, both aboveground and belowground biomass, and carbon stock were processed using Microsoft Excel 2010 and R Software Version 3.2.2 for one-way analysis of variance (ANOVA).

RESULTS

Forest carbon stocks at each Church Forest

Carbon stock of Montogera Estifanos Church Forest

The results revealed that the mean aboveground biomass, carbon stock stored, and corresponding CO_2 equivalents were 125.03, 58.76 and 215.66 ton/ha, respectively. The minimum and maximum carbon densities with values of 5.06 and 129.34 ton/ha were estimated, respectively. Accordingly, minimum and maximum values of 18.57 and 474.68 ton/ha CO_2 equivalents were stored in aboveground biomass. The results revealed that the mean below ground biomass, carbon stock, and corresponding CO_2 equivalents in the forest were 32.51, 15.28 and 56.07 ton/ha, respectively. The minimum and maximum carbon densities with the value of 1.32 and 33.63 ton/ha respectively, were estimated. Accordingly, minimum and maximum of 4.83 and 123.42 ton/ha corresponding CO_2 equivalents were stored in belowground biomass. The results showed that the mean litter carbon stock and corresponding CO_2 were 2.37 and 8.69 ton/ha, respectively. In the soil carbon pool, the results showed that the mean soil organic carbon stock contained in it was 76.52 ton/ha. Accordingly, minimum and maximum values of 178.40 and 396.16 ton/ha with a mean of 280.82 corresponding CO_2 equivalents were stored in the soil. The total mean carbon stock (ton/ha) of Montogera Estifanos Church Forest, which is the sum of AGC, BGC, litter, and soil organic carbon (ton/ha), was 152.93 ton/ha. The corresponding minimum and maximum values of CO_2 equivalents were 206.17 and 897.23 ton/ha, with a mean of 561.24, respectively.

Carbon stock of Woji Abune Aregawi Debere Bereket Church Forest

The results revealed that the mean aboveground biomass, stored carbon stock and corresponding CO_2 equivalents were 71.19, 33.46 and 122.79 ton/ha, respectively. The minimum and maximum carbon densities with values of 4.69 and 87.71 ton/ha were estimated, respectively. Accordingly, minimum and maximum values of 17.20 and 321.90 ton/ha CO_2 equivalents were stored in aboveground biomass. The mean below ground biomass, carbon stock and corresponding CO_2 equivalent in the forest were 18.51, 8.70 and 31.93 ton/ha, respectively. The minimum and maximum carbon densities with values of 1.22 and 22.80 ton/ha respectively, were estimated. Accordingly, minimum and maximum of 4.47 and 83.69 ton/ha corresponding CO_2 equivalents were stored in belowground biomass. The results showed the mean litter carbon stock and corresponding CO_2 were 2.16 and 7.96 ton/ha, respectively.

In the soil carbon pool, the results showed the mean soil organic carbon stock contained in it was 86.33 ton/ha. Accordingly, minimum and maximum values of 145.74 and 569.53 ton/ha with a mean of 316.85 corresponding CO_2 equivalents were stored in the soil. The total carbon stock (ton/ha) of Woji Abune Aregawi Debere Bereket Church Forest, which is the sum of AGC, BGC, litter, and soil organic carbon (ton/ha) was 130.66 ton/ha. The carbon stocks in the plots ranged in the minimum value of 46.79 ton/ha and maximum values of 269.47 ton/ha forest zone. The

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corresponding minimum and maximum values of CO_2 equivalents were 172.37 and 988.95 ton/ha, with a mean of 453.60, respectively.

Carbon stock of Mai-Anbesa Kidane Miheret Monastery Forest

The results revealed that the mean above ground biomass, stored carbon stock, and corresponding CO_2 equivalent were 12.00, 6.00 and 22.03 ton/ha, respectively. The minimum and maximum carbon densities with values of 0.07 and 55.79 ton/ha were estimated, respectively. Accordingly, minimum and maximum values of 0.27 and 204.76 ton/ha CO_2 equivalents were stored in aboveground biomass. The results revealed that the mean belowground biomass, carbon stock, and corresponding CO_2 equivalent in the forest were 3.12, 1.47 and 5.38 ton/ha, respectively. The minimum and maximum carbon densities with values of 0.02 and 13.64 ton/ha were respectively, estimated. Accordingly, minimum and maximum of 0.07 and 50.4 ton/ha corresponding CO_2 equivalents were stored in belowground biomass. The results showed that the mean litter carbon stock and corresponding CO_2 were 1.33 and 4.90 ton/ha, respectively.

In the soil carbon pool, the results showed that the mean soil organic carbon stock contained in it was 121.90 ton/ha. Accordingly, minimum and maximum values of 335.28 and 562.84 ton/ha with a mean of 447.38 corresponding CO_2 equivalents were stored in the soil. The total mean carbon stock (ton/ha) of the Mai-Anbesa Kidane Miheret Monastery Forest, which is the sum of the AGC, BGC, litter, and soil organic carbon (ton/ha) was, 130.71 ton/ha. The corresponding minimum and maximum values of CO_2 equivalents were 337.48 and 829.17 ton/ha, with a mean of 479.69, respectively.

Carbon stock of Emba Kidest Arsema Mekane Andinet Monastery Forest

The results revealed that the mean above ground biomass, stored carbon stock and corresponding CO_2 equivalents were 1.50, 0.71 and 2.59 ton/ha, respectively. The minimum and maximum carbon densities with values of 0.27 and 1.60 ton/ha were respectively, estimated. Accordingly, minimum and maximum values of 0.99 and 5.85 ton/ha CO_2 equivalents were stored in aboveground biomass. The results revealed that the mean belowground biomass, carbon stock and, corresponding CO_2 equivalents in the forest were 0.39, 0.18 and 0.64 ton/ha, respectively. The minimum and maximum carbon densities with values of 0.07 and 0.41 ton/ha respectively, were estimated. Accordingly, minimum and maximum values of 0.24 and 1.44 ton/ha corresponding to CO_2 equivalents were stored in belowground biomass. The results showed that the mean litter carbon stock and corresponding CO_2 were 1.33 and 4.90 ton/ha respectively. In the soil carbon pool, the results showed that the mean soil organic carbon stock contained in it was 116.01 ton/ha. Accordingly, minimum and maximum values of 316.46 and 462.57 ton/ha with a mean of 425.76 corresponding CO_2 equivalents were stored in the soil. The total mean carbon stock (ton/ha) of Emba Kidest Arsema Mekane Andinet Monastery Forest, which is the sum of AGC, BGC, litter, and soil organic carbon (ton/ha) was 118.24 ton/ha. The corresponding minimum and maximum values of CO_2 equivalents were 320.28 and 473.86 ton/ha, respectively with a mean of 433.89

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ton/ha.

The total mean carbon storage of this forest was calculated as 133.14 tons $ha^{-1.}$
The potential of each study site in carbon stocks varies from site to site due to the area coverage and structure and vegetation composition of the tree/shrub species.

Table 1. The means value of the carbon stock in all study sites.

Study sites	AGC	BGC	LC	SOC	TOTAL
Woji Abune Aregawi Debere Bereket Church Forest	33.46	8.70	2.16	86.33	130.66
Montogera Estifanos Church Forest	58.76	15.28	2.37	76.52	152.93
Mai-Anbesa Kidane Miheret Monastery Forest	6.00	1.47	1.33	121.90	130.71
Emba Kidest Arsema Mekane Andinet Monastery Forest	0.71	0.18	1.33	116.01	118.24
Mean	24.73	6.41	1.80	100.19	133.14

The carbon stock potentials of Mai- Anbesa Kidane Miheret Monastery Forest and Emba Kidest Arsema Mekane Kidusan Andinet Monastery Forest were higher than those of other sites by soil organic carbon stock amount, but the carbon stock of the sites was lower than that of the rest of the study sites in both the AGC and BGC stocks (Figure 9). Therefore, Montogera Estifanos Church Forest has a higher carbon stock than compared to the rest of the study sites, while Emba Kidest Arsema Mekane Kidusan Andinet Monastery Forest has a lower carbon stock.

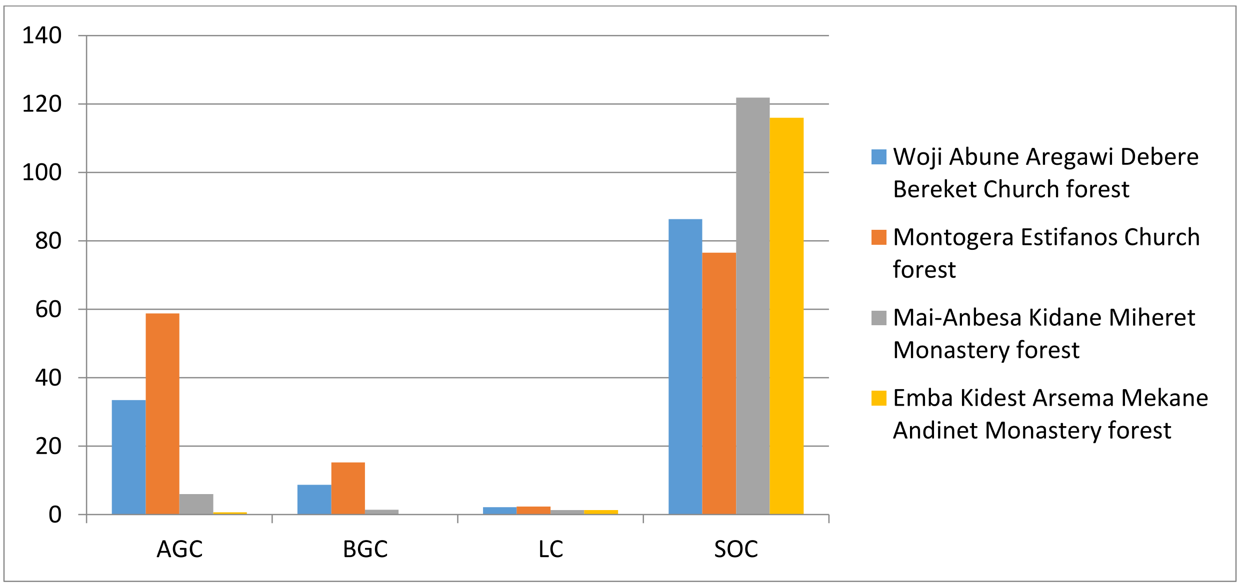

Figure 9. Total carbon stocks at study sites

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Carbon stock along altitude and site

In the present study area, the different carbon pools carbon stock above and belowground of trees, LHGs and carbon in soil were distributed along the altitudinal gradient, but the result revealed that there was no statistically significant variation of carbon stock in carbon pools along an altitudinal gradient (Table 2). The analysis of variance also revealed that there was a significant difference among the different carbon pools at the sites (Table 2).Table 2. Summarized results of two-way ANOVA relation between carbon pools with altitude and site

Gradient	Carbon stock			
Site	AGC	BGC	LC	SOC
F-value	16.89	8.762	8.753	6.944
P-value	7.29e-08 ***	1e-07 ***	7.47e-05 ***	0.000743 ***
Altitude				
F-value	1.876	2.274	1.945	0.542
P-value	0.177	0.137	0.143	0.852

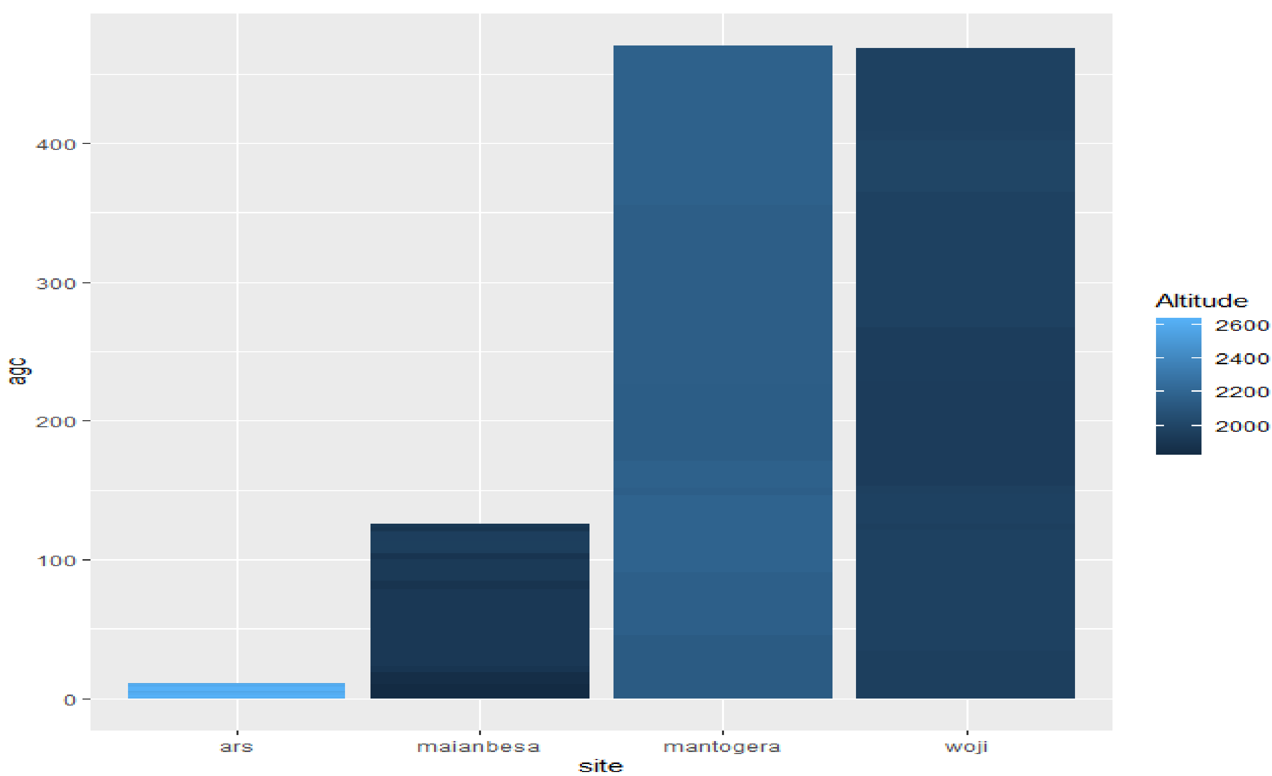

Figure 10. Visual representation of site with agc and altitude

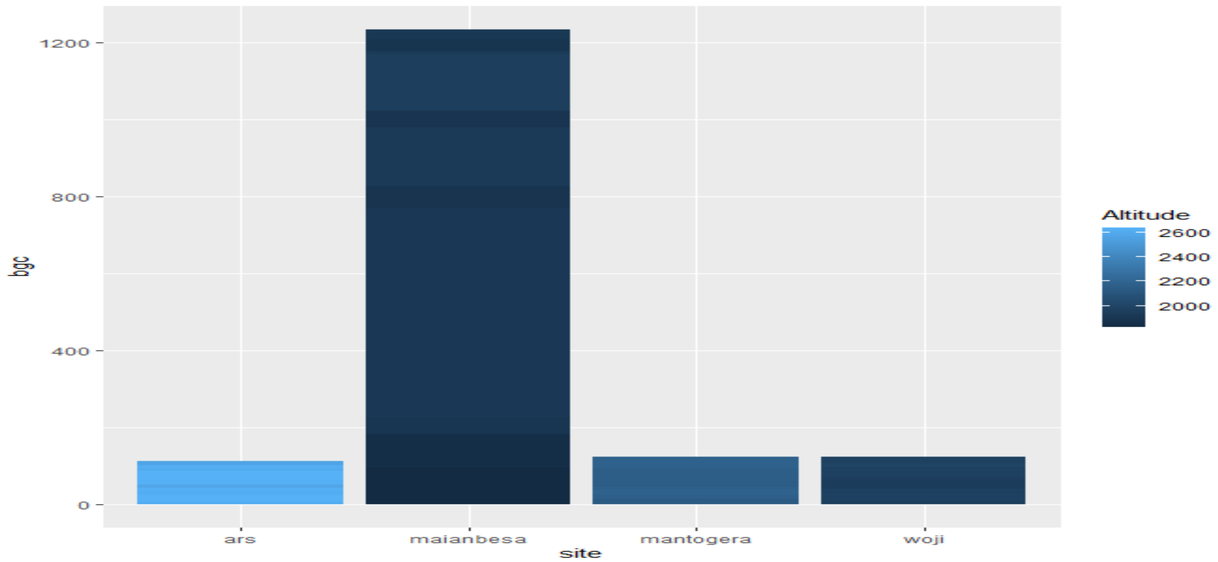

Figure 11. Visual representation of site with bgc and altitude

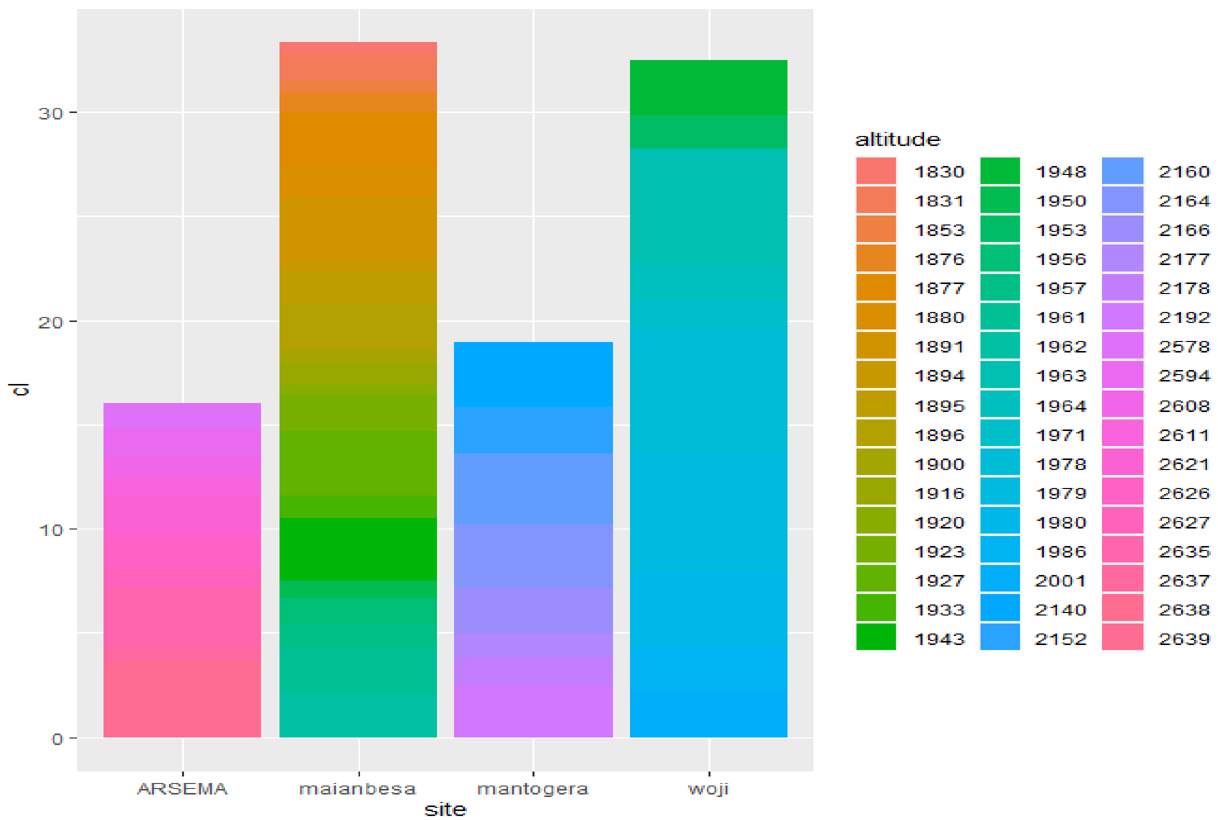

Figure 12. Visual representation of sites with LC and altitude

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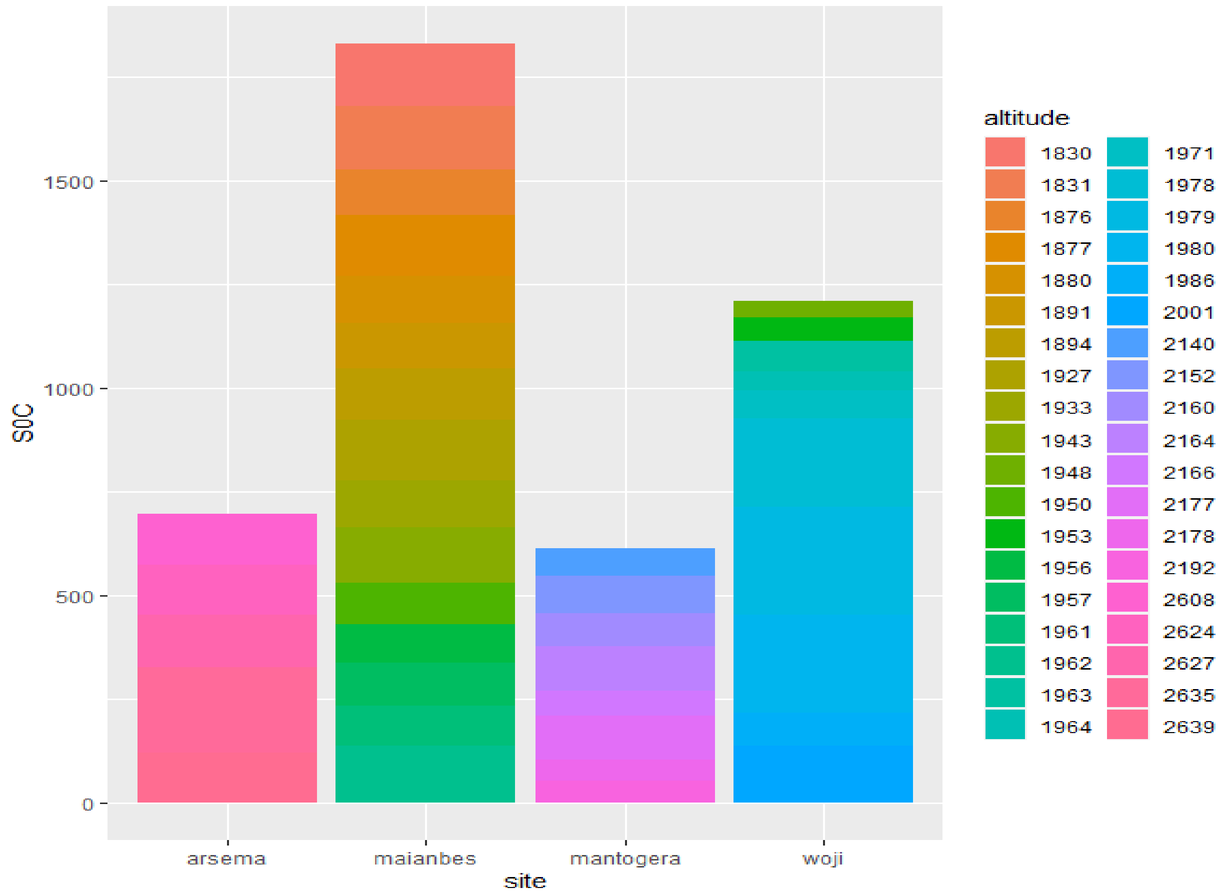

Figure 13. Visual representation of sites with SOC and altitude

DISCUSSION

The studied forest patches were endowed and characterized by important woody and shrub species in northern Ethiopia. They are one of the very few remaining dry Afromontane Church forests located in the Northern Highlands of Ethiopia. In addition, the types of plant species observed and identified at the sites were dominant and important woody species that could be used for the ecological benefit of the country at large.

According to Brown (1997), the aboveground carbon stock is 47 t/ha for tropical dry forests and 36 t/ha for sub-Saharan African countries, while, according to the IPCC (2006) assessment, 126 t/ha was reported for tropical dry forests and 72 t/ha for open sub-Saharan African countries. Similarly, Houghton (1999) recorded 55 t/ha carbon for tropical dry forests and 30 t/ha carbon for open forest in sub- Saharan African countries. The average aboveground carbon in the present study (24.73 t/ha) was smaller than the value indicated above.

Similarly, when compared with other studies, the mean carbon stock in above and belowground biomass of the present study was significantly lower than the result of Sekele-Mariam Dry Evergreen Montane Forest (Mekonnen and Tolera, 2019), Abiyu, & Tolla, Selected Church Forests (2013,2011 respectively). The BGC has a similar pattern to that of the aboveground values because it is 0.26 times (26%) that of the aboveground results. This difference in the carbon stock of the forest site is probably due to variations in the age of the trees, management of the forests, allometric model used, regional variability in soil, topography, existing species height, and DBH range of trees, and that few large individuals can account for a large proportion of the plots above and belowground carbon (Brown and Lugo, 1982).

According to Brown and Lugo (1982), litter fall in dry tropical forests ranges between 2.52- 3.69 t ha^{-1} $year^{-1}$. On the other hand, the mean biomass carbon stock in LHGs for tropical dry forests was 2.1 t/ha, as reported by the IPCC (2006). The findings of the present study were less compared to the values reported above. The mean carbon stock of litter biomass obtained in this study was also lower than Selected Church Forests (Tola, 2011), but was higher than the result of Sekele-Mariam Dry Evergreen Montane Forest (0.02-ton ha^{-1}) reported by Mekonnen and Tolera (2019), and selected Church forests (0.9 ton/ha) reported by Abiyu, (2013). The reason for litter carbon differences may be due to factors such as the rate of decomposition (which is governed by climatic factors such as temperature and moisture), forest vegetation type (species, age and density), land cover types, and climate (Binkley and Fisher, 2013). Furthermore, the variation might have happened due to differences in forest management practices of the Church forests.

Soil organic carbon plays a vital role in the global carbon cycle and C pools (Sundarapandian and Subbiah, 2015). According to Luke (2018), the average soil organic carbon in Ethiopia ranges from 94 to 133 ton/ha. On the other hand, the IPCC default values are 31 to 130 ton/ha for different tropical soils (IPCC, 2006). This result obtained from the present study was consistent with the studies mentioned above. This finding was more or less similar to the findings reported by Abiyu, (2013), Mekonnen and Tolera, (2019) and Tola, (2011). The contribution of the SOC stock was higher than the total biomass contribution.

Forests are one of the crucial ecosystem components that play a great role in temporary and long-term carbon storage, but forest biomass and carbon are highly disturbed by environmental factors such as altitude (Asner *et al*., 2014 and Fentahun *et al.*, 2017).

The maximum AGC (t/ha) was found in the Montogera Estifanos Church Forest. The variation may have occurred due to tree diameter and height. This implies that the higher carbon stock in above-ground biomass at the study site could be related to higher tree DBH in the Church Forest. According to Slik *et al.*, (2013) larger trees have a significant role in variability in carbon stocks. This is also supported by Gibbs *et al*.,(2007), who reported larger trees with higher diameters storing the largest density of carbon within biomass. Another study suggested that the large tree

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led to an increase in carbon stocks, while the smaller size classes contributed to a small fraction of the live AGC (Getaneh *et al*., 2019).

SOC is determined by solar radiation, ground vegetation, biomass content, and microbial activities. One aspect of the organic carbon pool that remains poorly understood is its vertical distribution in the soil and accompanying its relationship with climate and vegetation (Jobbágy & Jackson, 2000). The increase in temperature leads to an increase in production and decomposition. In addition, high altitude plants have a large root- to- shoot ratio, which results in a higher carbon concentration in the soil (Yang *et al*., 2009). Soil organic carbon has been shown to increase with increased clay contents (Jobbágy & Jackson, 2000) because clay dominated soils are capable of higher SOC storage than coarse-textured sandy soils due to stabilizing effects of soil macro aggregates and associated iron oxides on soil organic matter (Six *et al*.,2000). These might be the reason for the variation in the SOC content at the study sites.

Generally, the carbon pool of the study sites did not show significant variation along the altitudinal gradient, such as aboveground carbon, belowground carbon, litter carbon, and soil organic carbon. The reason for this might be due to the similar species composition and topographical nature where the study sites were located throughout the altitudinal gradient of the forest.

CONCLUSIONS

The mean carbon stock density obtained for the Church forests was 133.14 ton/ha. Although the carbon stock in the study sites was relatively low compared to that in similar Church forests in the country, the characteristics of plant communities in the study area present good carbon stocks, especially, in soils and woody biomass. In addition, there was tremendous capacity for the study area to store carbon and act as a carbon sink if properly managed
.

Differences in carbon storage among the studied Church forests reflect variation in a number of factors, such as tree community physiognomic characteristics, composition, and soil properties. DBH is the most significant factor for large aboveground biomass storage in Mantogera Church Forest. The mean carbon stock in the respective pools showed that the soil carbon pool was the highest, followed by aboveground biomass while litter had a lower carbon stock.In this study, aboveground, belowground, soil carbon, and litter carbon pools were not significantly different along altitudinal gradients.Finally, forest carbon-related awareness creation for local people, and promotion of local knowledge can be regarded as possible options for sustainable forest management.

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Authors' contributions
kehali has wrote the paper and did the analysis. Teshome Soromessa has reviewed the paper, and helped write it. Abeje Eshete has reviewed the paper, and edited the grammar. The authors read and approved the final manuscript.

Competing interests
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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