Tree Biomass Carbon in different Land Use Types Managed by Smallholder Farmers Along Altitudinal Gradient in Central Highlands of Ethiopia

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Abstract

Background and Aims Biomass carbon (C) stocks of trees across three common traditional agroforestry practices (i.e. home-garden, farmland, and grazing land) and along altitudinal gradients (i.e. upper, middle and lower) in southern Ethiopia are presented and evaluated. These traditional AF systems are characterized by a high proportion and diversity of trees hence can play a remarkable role in climate change adaptation and mitigation.

Methods Data were collected from a total of 89 plots: 41 home-gardens, 29 croplands, and 19 grazing lands using total count and Y-frame transect sampling methods. Above- and belowground biomass of trees were calculated using allometric equations developed somewhere else but proven for application in agroforestry systems. Trees with DBH ≥ 2 cm were considered for biomass carbon stock determination.

Results above-ground biomass carbon stock of the three land uses showed the order: Home-garden > grazing land > cropland, but the differences in the carbon stocks were not statistically significant. Soil carbon stocks measured from the studied land uses at middle altitude also followed a similar trend. Similarly, differences among altitudinal gradients were not statistically significant. However, the variations observed reflected differences in species composition among the system as well as altitudinal gradients. Other factors such as wealth and garden size also significantly affected biomass C stocks per ha, where rich household holds higher above-ground biomass than medium and poor households. Overall, this reflects that rich households own a large parcel and large total number of trees, compared to that of medium and poor wealth classes.

Conclusions The biomass C stocks of the tree across the three studied AF systems were found to be lower than reported for tropical forests and agro-forestry systems due to the recently agro-forestry intensification in the form of reduction in tree diversity and density. For enhancing their biomass carbon stocks traditional agro-forestry should be integrated in future REDD+ projects. As the biomass C stocks were more determined by socioeconomic factors such as wealth and garden size than the types of agro-forestry practice and climate (elevation) future carbon management strategies should also considered them.

Introduction

Climate change is a worldwide concern of humanity and it should be mitigated with all possible efforts and technologies (Stavi and Lal, 2013). Deforestation, forest degradation, and land-use changes are among major anthropogenic activities contributing to global climate change. Agricultural practices are the significant driver of deforestation and consequently leading to emissions of large amounts of greenhouse gases (GHGs), mainly carbon dioxide (CO_2), which is responsible for global warming (Stocker et al. 2013). For instance, between 1990 and 2014 annual agricultural emissions from African agriculture increased by 46.4% from 569.3 to 833.6 Mega-tons of carbon dioxide equivalents (Mt CO2e), making up nearly 16% of global agricultural emissions over the period(FAO, 2017).

As much they are the cause, agricultural systems and landscapes can also offer opportunities for mitigating climate change by increasing the number of trees in and around farms (Roshetko et al. 2002; Zomer et al. 2009). Traditional agroforestry practices are among agricultural systems with such an opportunity. Globally, 46% of all agricultural land is covered at least by about 10% tree (Zomer et al. 2016). These on-farm trees can serve as a sink for CO_2 (Henry et al. 2009; Negash and Starr, 2015). They contribute not only to sequestration and storage of carbon but also reduce fossil-fuel burning by providing alternative sources of wood products otherwise derived through deforestation and forest degradation (Kumar and Nair, 2004). Agroforestry practices also play an important role in conserving biodiversity (Bishaw et al. 2013). They can also provide substantial co-benefits in enhancing resilience (adaptation) to climate change and rainfall variability by improving soil fertility, thereby increasing productivity and diversifying farm income (Dhyani 2014; Kahiluoto et al. 2014; Lasco et al. 2014; Mbow et al. 2014a; Haile et al. 2017).

Agroforestry is the third-largest C sink after primary forests, followed by long-term fallows in Africa (Mbow et al. 2014b). In agroforestry, trees store about 3 to 4 fold higher carbon stocks than crop and pasture lands without trees, with C stocks ranging from 29–228 Mg ha^{-1} (Matocha et al. 2012; Mbow et al. 2014). On a global scale, the total land area under different types of agroforestry systems is about 1.6 billion hectares, with a carbon sequestration potential of 1.1–2.2 Pg C over the next 50 years (Lorenz and Lal 2014). And if the same is expanded on 630 million ha of currently degraded and underutilized grazing- and croplands, an additional 586,000 Mg C yr^{-1} could be added by 2040 (Kumar and Nair 2011).

In Ethiopia, millions of smallholder farmers practice a traditional agroforestry system with varying intensities of tree density. Common traditional agroforestry practices recognized in the country comprise multistory home-garden, parkland agroforestry, coffee shade agroforestry, live fence, woodlots, and many other forms (Duguma and Hager, 2010; Haile et al. 2017; Chiemela et al. 2017). Trees in these agroforestry systems provide multiple economic, social, and ecological services, which include climate change mitigation and adaptation. On farm trees can also provide substantial co-benefits in enhancing resilience (adaptation) to climate change and rainfall variability by improving soil carbon stocks thereby increasing crop productivity and diversifying farm income.

The magnitude and potential of the system for carbon sequestration could vary depending on the land use, tree management practices, species composition, tree density, and other factors (Albrecht and Kandji, 2003; Henry et al. 2009; Luedeling et al. 2011). Besides, environmental factors such as climate type, altitude, and topography (slope and aspect) could influence the magnitude of carbon storage (Roshetko et al. 2002; Albrecht and Kandji, 2003; Haile et al. 2017; Gebrewahid et al. 2018). For instance, Leuschner et al. (2007) and Zhu et al. (2010) found a declining trend of above-ground tree biomass and carbon stock with increasing altitudinal gradients, whereas Gebrewahid et al. (2018) reported the opposite. Socio-economic factors such as landholding size and wealth status are also likely to affect the tree stem density and their associated biomass carbon stocks (Kumar, 2011; Haile et al. 2017). Moreover, recently agro-forest intensification in the form of reduction in shade tree diversity, density and replacement with annual copping reduces their carbon storage capacity.

In this study we opted to: (1) quantify biomass carbon stock of three traditional agroforestry land uses (home-garden, farmland, and grazing land) across altitudinal gradients (upper, middle, and lower); (2) determine the relationship between tree diversity and biomass carbon stock; and (3) examine how landholding size and household wealth status impact aboveground C sequestration in the studied home-gardens.

Materials And Methods

Location and description of the study area

This study was conducted in Meskane district of Gurage Zone, which is located between 38°15'0.7"-38°33'50.9" E longitude and 8°1' 58.8" - 8°16' 29.6" N latitude in Southern Nations, Nationalities and Peoples Regional State, Ethiopia (SNNPRS) (Figure 1). The district covers an area of 50177 ha and is characterized by an altitudinal range of 1700 to 3500 m above sea level (a.s.l.) and has various topographic features consisting of plain (55%), sloppy (35%), and mountainous land (10%) (Haile et al. 2017).

Subsistence-oriented crop-livestock farming system or mixed farming system is the main agricultural practice in the study area.. The most commonly grown annual crops include maize, teff, wheat, pulse, and sorghum. Perennial crops like enset (*Enset ventricosum* (Welw.) Cheesman) and coffee (*Coffee arabica*) are also dominantly grown close to homestead. Livestock production is also a major source of livelihood. Farmers are rearing diverse livestock including cattle, horses, donkeys, goats, sheep, mule, and poultry. According to the Ethiopian climate classification, the study area belongs to Weynadega and Dega tropical continental climate, which account for about 74% and 26%, respectively. Dega agro-ecology is characterized by high rainfall, while Weynadega receives moderate rainfall. The area is characterized by bimodal rainfall, which receives rain from March to September, with major rains usually occurring in July and August (Fig. 2). The average mean annual rainfall was 1167 mm and the mean monthly maximum and minimum temperatures were 27.3^{o}C and 10^{o}C, respectively (Fig. 2).

Soils of the study sites include eutric Cambisols, chromic Luvisols, pellic Vertisols, chromic Vertisols, eutric Fluvisols, and Leptosols (FAO, 2015). In terms of texture, 47% of the soil is sandy loam while the remaining 38% and 15% is clay loam and clay, respectively (WARD, 2016). Based on soil color, soils of the study area were classified into three major groups, black, brown and red soils which accounts for about 53%, 25%, and 22%, respectively (WARD, 2016).

The study area has diverse land uses that resulted due to differences in climate, population density, economic opportunities, cultural practices, and depletion of soil nutrients. Moreover, high population growth and land fragmentation are the major problems in the study area. Consequently, many farmers in the study area are using their holdings by partitioning into different land-use types like grazing land, cereal farmland, home-garden, and Eucalyptus woodlot to diversify their farm produces and to reduce risk (Haile et al. 2016). The distribution of the major land uses of the studied farmers were farmland (52.68%), home-garden (26.49), grazing land (12.68%), and woodlots (8.17%) (Haile et al., 2017). At the district level, the pattern of land use/land cover includes cultivated land of 23234 ha (46%), forest land 10093 ha (20%), grazing land 3346 ha (7%), wasteland 1801 ha (4%), settlements, road, and other uses 11703 ha (23%). Regarding tree vegetation, smallholder farmers commonly plant and/or retain diverse native tree species in and around their farm. The major tree species growing in the study area are *Cordia africana, Juniperus procera, Croton macrostachys, Prunus africana, Acacia abyssinica, Acacia seyal, Fiaderbia albida,* and *Acaica sieberiana*. Fruit trees such as *Persea Americana*, *Mangifera indica,* and Citrus spp. are also commonly grown around homesteads (Haile et al. 2017). Economically important exotic tree species such as *Eucalyptus camaldulensis, Cupressus lusitanica,* and *Grevillea robusta* are also grown and managed widely. In the study area, upper altitude maintains higher tree diversity than middle and lower altitude areas due to the relatively good rainfall and the unsuitability of the terrain conditions for annual cereal cropping and the presence of adjacent fragmented natural forest patch (Haile et al. 2017). Among the major land= use types, home-gardens of the study area hosted a higher number of tree species than other land-use types due to intensive management and better security from free grazing, theft, and land tenure security (Haile et al. 2017). In the study area, farmers who had a large parcel of land planted Eucalyptus trees in the form of woodlots in separate plots far from homestead , especially in the middle and lower altitude, but trees measured from this land use was not considered for biomass carbon estimation in the current study.

Sampling design

A stratified sampling method was used to select study farms within the different traditional agroforestry land=use systems identified in the study area. The study site was stratified into three altitudinal zones: lower (1800 to 2000m), middle (2000 to 2200 m), and upper (2200 to 2400 m a.s.l) to capture the heterogeneity of sites (i.e. soil conditions, climate, and topography). From each zone, one Kebele (i.e. the smallest administrative unit in Ethiopia) was randomly selected (Fig. 1). Three geo-referenced points were chosen from each Kebele to locate the centre of the Y-frame with the aid of a GPS. From each geo-referenced point, a Y-frame transect line was established in the manner done by Henry et al. (2009). The frame had a radius of 900 m and included 13 farms along 3 transect line diverting at 120 degrees from each other. Then a farm in the center of the frame and four farms on each transect line at 100, 300, 600, and 900 m from the centre were selected for the study (Fig. 1).

The selected farms were further categorized into three land-use types such as home-garden, cropland, and grazing land. Home-garden— is the land use type that is close to home often bounded by a live fence, and in which gardening and farming are practiced. Home-garden is a typically poly-culture consisting of hedgerow/ boundary planting, a field with annual crops; grazing field, and enset field, fruit trees/orchard, and Eucalyptus woodlots and other economically important cash crops like *Catha edulis* and *Coffee arabica*. Cropland is a field far from home and dominantly covered by cereal crops, and often scattered native trees are commonly found in and around the field for enhancing soil fertility, shading and tree products, and boundary plantings. Grazing land is degraded land devoted for grazing and used for growing grass for livestock feed and some scattered native trees are retained in and around it as shade for livestock and as boundary planting.

The effect of garden size on biomass carbon stocks was determined based on biomass data measured from a total of 41 home-gardens. The selected gardens were further categorized based on their size into small (< 0. 5 ha), medium (≥ 0.5 < 1 ha), and large (≥ 1 ha). Further, for assessing the effects of household wealth status on biomass carbon storage, the selected households were classified into three wealth classes (poor, medium, and rich) based on local criteria such as landholding size, housing status, and livestock holdings. Equal numbers of households from each wealth class were selected. A total of 39 (i.e. 13 poor, 13 medium, and 13 rich) households were selected. The characteristics of the three altitudinal gradients, socioeconomic status of the households, and other details of the studied sites were described by Haile et al. (2017). Information on landholding size, household wealth status, and other socioeconomic parameters were gathered during the household survey and verified through inventory.

Data collection

The on-farm tree measurement (inventory) was carried out on a total of 89 plots, i.e. 41 home-gardens, 29 croplands, and 19 grazing lands. In a situation where a farmer owns more than one plot of a similar type, measurements were made from all plots/fields and averaged for analysis. On each plot, all trees with a diameter of ≥2 cm and height of ≥1.5 m were counted and measured for their DBH and height using a caliper and/or a diameter tape and hypsometers, respectively. Stem diameter (DBH) were measured in two perpendicular directions and averaged. In the case of multi-stemmed trees, each stem was measured and the equivalent diameter of the tree was calculated as the square root of the sum of diameters of all stems per tree in the manner done by Snowdon et al. (2002). Tree density or stocking was determined by dividing the number of tree stems by the area of the plots.

Species of the trees encountered were identified in the field based on vernacular names and using supplementary field guide (Bekele, 2007). For species difficult to identify in the field, specimens were collected and taken to the National Herbarium at Addis Ababa University for identification. Tree species identification followed the flora of Ethiopia and Eritrea volume 1-8 (Edwards et al. 1995; Hedberg et al. 2004).

The above-ground tree biomass and carbon stocks were estimated. Local-level and species-specific biomass allometric equations for trees in agricultural landscapes and/or agroforestry tree species are scanty in Ethiopia (Negash et al. 2013a,b and Zewdie, 2008). Hence, in this study, the tree above-ground biomass (AGB) was estimated using an allometric model developed somewhere else but proven for wider application. This was also because developing new tree species-specific allometric equations through destructive sampling methods is costly, labor-intensive and time taking. Moreover, many tropical agroforestry systems, including our study sites host diverse tree species and this makes it difficult to use species-specific regression models to estimate biomass and carbon stocks (Brown and Schroeder, 1999; Haile et al. 2017). Therefore, the allometric equation developed by Kuyah et al. (2012) was employed for this study:

$AGB = 0{:}225 * dbh^{2:341} * \rho^{0:73}$

Where:

- AGB is the estimation of the aboveground biomass (kg dry matter/plant)
- dbh is the diameter (cm) at breast height (1.3 m), and
- ρ is species wood density (g cm^{-3}).

This equation was selected as it was used for biomass estimation in agroforestry systems in Malawi (Kuyah et al. 2014) and south-eastern Ethiopia (Seta and Demissew, 2014; Negash and Starr, 2015) and Northern Ethiopia (Gebrewahid et al. 2018). Moreover, this equation is developed for trees growing in agricultural landscapes having DBH greater than 3 cm in Western Kenya. Wood densities (ρ) were retrieved from the online databases (ICRAF, 2015; Zanne et al. 2009). If species-level data was not available, mean genus-level values were used.

Trees biomass was converted to carbon using the default values of the Intergovernmental Panel on Climate Change (IPCC) value of 0.47 (IPCC, 2006). The AGB carbon stock was calculated for each tree and was aggregated to calculate the total AGB carbon stock for each land use and altitudinal categories. For comparisons on a unit area basis, the values were extrapolated to a hectare. The CO_2e of each land use system and the altitudinal category was calculated by multiplying the total C stock of each land-use system (biomass carbon stocks each system) by a factor of 3.67 (IPCC, 2003).

Soil carbon stocks measured in previous study from middle altitude the studied are presented and evaluated (Table 2).

Data analysis

Two-way analysis of variance (ANOVA) was used to investigate the effects of land-use types and altitudinal classes and their interaction on Above-ground biomass carbon(AG) Both altitude and land use types included three levels. Altitude comprised (upper, middle, and lower) and land-use comprised (home-garden, croplands and grazing land), respectively. One-way ANOVA was also used to determine the effects of garden size and wealth status on AGC in home-garden. To meet the assumptions of normal distribution and homogeneity of variances, data on aboveground biomass C were log-transformed before statistical analysis was undertaken and reported after back transformation. All statistical computations were made using IBM-SPSS statistical software (version 21) (IBM Corp. Released 2012). When the ANOVA showed a significant difference ($p < 0.05$) among size of gardens, household wealth status, land-use types, altitudinal categories, and their interaction, mean separation was made using Turkey’s pairwise comparisons. Pearson statistical tests were performed to test the relationship between AGC and tree biodiversity (e.g. Shannon, Simpson, and Evenness and species richness) and other vegetation data such as basal area, tree stocking, or tree stem per ha.

Results And Discussion

Aboveground carbon stock across land-use types and elevation gradients

The AGC stock showed significant variation among land-use types (Table 3) but not with altitudinal gradients. The combined effect of altitude and land use also showed a significant effect on AGC stock (p = 0.009). The AGC stock in home-garden was significantly higher than that of grazing land and cropland. Home-gardens had 121.7 and 86.3 Mg/ha more AGC than cropland and grazing-land, respectively (Table 3). Cropland hosts low AGC because of the lesser number of trees compared to the other land-use types, where reduction of resource competition with cereal crops requires. Conversely, higher biomass carbon stock in home-garden than grazing land justifies the greater occurrence of trees in these land-use systems (Haile et al. 2017). A previous study reported 237.3 stems/ha in home-gardens compared to 41.4 stems/ha in grazing-land and only 14.8 stems/ha in cropland in the study area (Haile et al. 2017). Henry et al. (2009) reported a similar finding in a comparative study they made of home-gardens, cash and food crops, and pasture land-use types. Soil organic carbon (SOC) was followed a decreasing trend of home-garden > grazing-land > crop land(Table 2). This indicates the potential of home-garden agro-forestry) for climate changes mitigation and adaption.

The AGC recorded in this study was higher than other studies of agroforestry systems such as those in southern Ethiopia (Negash and Starr, 2015; Seta and Demissew, 2014), and those in western Kenya (Henry et al. 2009) and Indonesia (Roshetko et al. 2002). This could be attributed to differences in tree management systems, elevation (topography and slope), climate (precipitation and temperature), biophysical features (soils and vegetation), and land-use. On the other hand, the carbon stock in this study was lower than reported for traditional agroforestry systems in the tropics (Kirby and Potvin, 2007) and smallholder agroforestry system in the tropics (Roshetko et al. 2007), and smallholders cacao-based agroforestry systems in western and central Africa (Duguma et al. 2001).

Biomass carbon stocks did not differ statistically significantly (p=0.458 Table 4) across altitudinal gradients, but in value terms, it followed the order: upper altitude > lower altitude > mid-altitude. The upper altitude had 33.6% and 5.3% higher mean AGC stock than mid and lower altitudinal classes, respectively (Table 4). These variations might be linked to the differences in tree management practice, soil fertility, and environmental variables. For example, farmers in upper altitude plant Eucalyptus in home-garden whereas in mid-altitude Eucalyptus is planted in separate plots far from home their contribution was not considered in latter cases. Soils and slopes in upper altitude are also unsuitable for cropping due to the presence of poor soil fertility and high relief intensity hence farmers preferred tree planting to crop production.

Haile et al. (2017) showed a higher number of tree densities per ha in mid-altitude (716.7 tree stems per ha) followed by upper altitude (682.95 tree stems per ha) and lower altitude (636.17 tree stems per ha). Gebrewahid et al. (2018) reported increasing AGC stocks of scattered trees on farmlands with increasing altitude in Tigray, northern Ethiopia. This result is different from the findings of Leuschner et al. (2007) and Zhu et al. (2010), who reported decreasing trends of AGC stock with increasing altitude. This may be due to the difference in the altitudinal range studied, climate (precipitation and temperature), biophysical features (soils and vegetation), and land-use and thus differences in tree species composition, biomass stock, and the like (Nair et al. 2009). Studies have also attested the influence of the tree density and tree species composition and size of trees (dbh) on standing biomass carbon stocks (Luedeling et al. 2011; Seta and Demissew, 2014; Chiemela et al. 2017).

Contribution of tree species' to AGC storage across land-use types and elevation categories

The contribution of tree species toward AGC storage varied across land-use types and elevation categories (Table 4). *E. camaldulensis* contributed the highest AGC of 44.82% in home-garden, while *A. abyssinica* was the highest contributor of AGC in grazing land (61.67%). *A. albida* and *A. abyssinica* were the maximum contributors of AGC which account for 42.9.9% and 33.58% of AGC in farm-land, respectively. The contribution of *E. camaldulensis* and *A. abyssinica* for AGC increased with increasing elevation gradient. The contribution of the *E. camaldulensis* for AGC showed a decreasing trend with a decreasing altitudinal gradient. *E. camaldulensis* contributed 44.58% in the upper altitude while in mid and lower altitude its contribution was 26.86% and 10.04% of AGC, respectively. Likewise, the contribution of *A. abyssinica* for AGC increased with increasing altitudinal gradients while that of *A. albida* showed the opposite trend.

Similarly, *E. camaldulensis* had the highest AGC density of 92.96 Mg/ha in home-garden followed by farmland and grazing lands (Table 5). However, *A. abyssinca* had the highest AGC of 64.89 Mg/ha in grazing land followed by home-garden and farmland. The AGC density of *E. camaldulensis* showed a decreasing trend with decreasing altitudinal gradients (i.e. 115.29 Mg/ha in upper, 39.4 Mg/ha in middle, and 10.5 Mg/ha in lower altitude) (Table 5). *A. abyssinica* also showed a similar trend of decreasing AGC density with decreasing altitude. This indicates that farmers deliberately plant and/ or retain a large number of multipurpose trees due to the high relief intensity and unsuitability of land for annual cropping in upper altitude. Moreover, farmers retain big=sized native tree species (e.g. *A. albida* in the farmland of lower altitude and *A. abyssinica* in the grazing land of upper altitude) resulted in higher biomass carbon stock. According to Abebe (2005), the density and standing stocks of trees in agroforestry practice vary with the tree growing location or niches. Moreover, the ecological distribution of the tree species could also influence the contribution of tree species for carbon sequestration. The measured AGC density of *A. abyssinica* was 101.39 Mg/ha in the upper elevation category and 50.12 Mg/ha in the middle category, and 0.14Mg/ha in lower elevation category (Table 4). In contrast, *A. albida* had a higher AGBC density of 31.86 Mg/ha in lower altitudes followed by middle and upper altitudinal categories (Table 5).

Among the identified tree species in the studied land uses, seven tree species contributed about 89.34% of the aboveground biomass carbon stocks. The seven tree species were *A. abyssinica*, *E.camaldulensis*, *A. albida*, *C. macrostachyus*, *A. seyal*, *A. sieberiana* and *C. africana* in decreasing order (Table 5). Of these *A. abyssinica,E. camaldulensis,* and *A. albida* were the highest AGC contributors, which account for 37.27%, 16.81%, and 15.55%, respectively. The higher contribution of these tree species may be associated with their high ecological and economic importance in the study area. Several studies reported that the effects of tree abundance and tree size (DBH) contributed to increasing C stocks (Henry et al. 2009; Kumar, 2011; Seta and Demeseiw, 2014). The results of our study are consistent with the finding of Henry et al. (2009) who reported about 68% of the contrition of trees to AGBC in Western Kenya. The findings of Negash and Starr (2015) and Gebrewahid et al. (2018) are also in agreement with the results of our study who reported about 39–93 % and 50% contribution of trees for AGC across home=garden agroforestry systems and trees scattered in cropland in southern and northern Ethiopia,, respectively

Tree biomass carbon in home-garden as affected by wealth and garden size

The AGC stocks on a unit area basis showed significant (*P = 0.000)* differences among household wealth status (Table 6). Gardens of rich households had 100.85 Mg C/ha more AGC than that of gardens of medium households and 49.42 Mg C/ha than that of gardens of poor households (Table 6). Likewise, standing biomass C stock of tree species per garden showed a similar increasing trend with increasing wealth status (Table 6). Previous studies in the study area showed an increasing trend of tree stems per ha with increasing household wealth status i.e. 1265.6 tree stems per ha in rich households while medium and poor households had 479 and 324.6 tree stems per ha, respectively (Haile et al. 2017).

This reflects that rich households possess an overall large parcel and a large total number of trees, compared to that of medium and poor wealth classes and consequently higher AGC. Other studies also witnessed the influence of household wealth status on biomass carbon through affecting holding size (Tschakert and Tappan, 2004), tree species composition, diversity, their abundance and dominance (Haile et al. 2017).

Apart from the effects of wealth status on biomass carbon stocks in home-gardens, an attempt was also made to investigate the variation of AGC in home-gardens due to differences in garden size. Accordingly, biomass carbon stock per unit area was significantly different due to variation in garden size. The overall mean AGBC stock per unit area was higher in large home-gardens, followed by the medium and small-sized gardens (Table 7). Large-sized gardens had 110.8% and 40.57% higher biomass carbon stocks (Mg/ha) than the small and medium gardens, respectively. This result is in conformity with the finding of Henry et al. (2009) who reported higher biomass carbon stocks in the larger farms than smaller and medium-sized farms in western Kenya. However, these results are different from the findings of Kumar (2011) and Jaman et al. (2016), who found a decreasing trend of biomass carbon per ha with increasing garden size in the order of small > medium > large in the home-gardens of central Kerala, India and Rangpur District of Bangladesh, respectively. Similarly biomass aboveground C stock per garden significantly ($p < 0.05$) varied due to the difference in garden size (Table 7). Biomass carbon stocks per home-garden increased in the order of large > medium > small-sized home-garden (Table 6). Large-sized gardens had 105.58 Mg/ha more AGC than small-sized gardens and 57.96 Mg C/ha more than medium-sized gardens (Table 7). The higher biomass carbon stock in large-sized gardens is generally associated with the presence of higher tree stem density, dominance, and tree species composition compared to the medium and small garden sizes.

Relationship between aboveground biomass carbon and tree diversity

It is assumed that biodiversity is one of among many factors influencing AGC stocks. However, in the current study, all the considered tree diversity indices such as Shannon, Simpson's, and evenness and tree species richness showed insignificant or weak correlation with AGC (Table 8). This result is similar to the finding of Henry et al. (2009), who reported a weak correlation between biomass carbon stocks and plant biodiversity in the agricultural landscapes of western Kenya. This result is also different from the findings of Thompson et al. (2012) and Seta and Demissew, (2014), who reported strong and positive correlations between species richness and aboveground biomass. The result of this study is also contradictory with the finding of Thokchom and Yadava (2017), who found a strong and positive correlation between stand density and aboveground carbon stock. This implies that higher tree species diversity doesn't necessarily associate with the increased tree standing C stocks in smallholder managed agroforestry systems due to high disturbance in the system (Richards and Mendez, 2014). However, the finding of Seta and Demissew (2014) conforms to the results of this study who found a weak correlation between tree density and aboveground carbon stock. However, the basal area had a significant positive relationship with AGC, with a correlation coefficient of 0.647^{**} (Table 8). Our results are also in line with the findings of Henry et al. (2009) and Mandal et al. (2013), who found significant and positive correlations between carbon stocks and basal area.

Conclusions

The results of this study showed that the AGC of tree species significantly varied with land-use types but not with elevation gradients. Home-gardens had higher biomass carbon stocks than grazing and farmlands. Soil carbon stock measured from middle altitude also followed a similar trend .The upper altitude had a higher biomass carbon stocks compared to the lower and middle altitude. Aboveground biomass C stock hosted in home-garden was significantly higher in large-sized gardens followed by the medium and small garden sizes. Further, based on the area of gardens where the trees were inventoried, rich households' garden had more biomass carbon than medium and poor households. The AGC showed a significant relationship with the basal area, but it was weakly correlated with tree species diversity indices, implying greater tree species richness is not necessarily associated with greater standing C stock. Besides, land use, altitude, wealth status, and garden size significantly altered AGC and should be considered in designing biomass carbon management strategies. *A. abyssinica*, *E. camaldulensis*, *A. albida*, *C. macrostachyus*, *A. seyal*, *A. sieberiana*, and *C. africana* were the highest contributor of AG C-stocks in the study area. In general, preserving trees in the traditional agroforestry land-use system, especially in home-garden will have dual benefits in fighting against climate changes while simultaneously enhancing the livelihoods of smallholders. However, incentive mechanisms are needed that assure smallholder farmers will benefit from selecting management practices that favor higher C stocks.

List Of Abbreviations

AGB- above-ground biomass

ANOVA- analysis of variance

CO_2-carbon dioxide

DBH- Diameter at breast height

GHGs- greenhouse gases

GPS- Global *Positioning* system

IPCC -Intergovernmental Panel on Climate Change

NMAE- National Meteorological Agency of Ethiopia

SNNPRS -Southern Nations, Nationalities and Peoples Regional State

Tree-Crop Interactions in Agro-forestry Systems :

WARD- Woreda Agriculture and Rural Development

Declarations

Authors' contributions

The first authors designed the methodology, collect field data, analyzed and write the manuscripts while second author contributed in designing sampling methods and reviewing the first manuscripts. Third and fourth authors contribute in reviewing the final manuscripts

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Conflict of interest

No conflict of interest among the authors

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Tables

Table 1
Some attributes of the study sites

Characteristics	**Attitudinal gradients(m asl)**		
	2200–2400	**20000 – 2200**	**1800–2000**
Slope (%)	20–30	10–15	5–8
Rainfall (mm)	400 to 1800mm	400 to 1800mm	400 to 1600 mm
Temperature	15°C to 25°C	15°C to 25°C	15°C to 28°C
Major soil types	Eutric Cambisols	Eutric Cambisols and chromic Vertisols	Chromic Vertisols
Mean farm size(ha)	1.1	1.21	1.48
Farming system	Enset based farming system	Enset based farming system	Cereal based farming system
Distinct canopy trees	*A. abyssinica*	*A. abyssinica*	*A. albdia*

Table 2
Soil carbon stocks across three common Home-garden, grazing land and crop land)

Soil Property	Soil layer	Land use types			P value	F value
		Home-garden	Grazing land	Crop land		
SOC(Mg/ha)	0–15	49.41 ± 2.0	36.47 ± 7.8	27.59 ± 2.24	10.379	0.000
	15–30	43.11 ± 4.91	28.06 ± 2.35	25.34 ± 3.38	21.075	0.000
	30–45	34.86 ± 4.17	24.05 ± 2.13	23.72 ± 6.97	1.265	0.273
	Mean	42.45 ± 2.5a	29.52 ± 2bc	25.55 ± 1.3c	8.836	0.000
	Total	127.36 ± 7.54a	88.57 ± 7.97bc	76.65 ± 3.8c		
Source Haile et al.,2017						

Table 3
AGC among three traditional agro-forestry land-use types

Biomass carbon stock	**Land-use types**				
	Home-garden	**Farmland**	**Grazing land**	**F**	**p value**
AGC (tons/ha)	152.51 ± 1.97a	30.78 ± 3.45b	66.22 ± 3.45b	24.784	0.000
AGC (tons CO_2e/ha)	545.75 ± 1.19a	112.85 ± 3.45b	243.09 ± 2.79b	27.53	0.000
AGC (tons/plot)	65.32 ± 2.45a	9.53 ± 4.23b	9.14 ± 4.8b	31.062	0.000
AGC (tons CO_2e/plot)	615.17 ± 2a	34.93 ± 4.23b	33.5 ± 4.8b	75.065	0.000

Table 4
AGBC as affected by upper, middle, and lower altitudinal categories

Biomass Carbon stock	**Altitudinal classes**				
	Upper	**Middle**	**Lower**	**F**	**p value**
AGBC/ha	82.98 ± 4.96a	62.11 ± 3.48a	78.83 ± 3.48a	0.858	0.429
AGB CO2/ha	304.29 ± 4.96a	242.10 ± 3.37a	316 ± 2.19a	2.1	0.132
AGBC/plot	48.74 ± 3.76a	17.5 ± 6.38b	19.13 ± 3.61b	9.561	0.000
AGB CO2/plot	245.47 ± 4.6a	92.26 ± 8.51b	128.20 ± 5.57ab	10.603	0.000

Table 5

Biomass carbon stock (Mg ha^{-1}) of major tree species across land-use and elevation gradients

Tree species	AGC storage (Mg/ha)					
	Land-use types			Altitudinal category		
	Homge-garden	Grazing land	Farm land	Upper	Middle	Lower
E. camaldulensis	92.96	1.16	2.87	115.29	39.4	10.5
A. abyssinica	34.32	64.89	12.18	101.39	50.12	0.14
C.africana	13.87	0.3	0.09	8.89	5.25	9.82
A. albida	7.38	0.18	15.57	0.01	0.23	31.86

Table 6

Effects of wealth status on tree aboveground carbon stocks in home-gardens

Carbon stocks	Household wealth status				
	Rich	Medium	Poor	F	p value
AGBC/ha	222 ± 2.5a	172.58 ± 2.17ab	121.3 ± 2.05a	10.612	0.000
AGBC CO_2/ha	814.33 ± 2.53a	677.79 ± 1.8a	443.81 ± 2.05a	10.612	0.000
AGBC/ garden	158.05 ± 1.93 a	51.17 ± 2.24b	36.07 ± 2.33b	1.769	0.188
AGBC CO_2/garden	579.43 ± 1.94a	187.67 ± 2.24b	132.25 ± 2.33b	1.769	0.188

Table 7

AGBC stocks (mean ± SD) (Mg ha^{-1}) as influenced by garden sizes in the study area.

Carbon stocks	Size of home-gardens				
	Large	Medium	Small	F	Pp value
AGBC per ha	200.82 ± 2.11b	142.86 ± 1.85ab	95.24 ± 1.39a	3.611	0.04
AGB CO2 per ha	737.56 ± 2.11b	524.32 ± 1.85ab	349.54 ± 1.39a	3.611	0.04
AGBC/ garden	114.36 ± 1.46 a	106.76 ± 1.98a	36.43 ± 2.32b	9.13	0.001
AGBC CO2/garden	419.37 ± 1.46	391.47 ± 1.98	133.72 ± 2.32	9.140	0.001

Table 8
Pearson correlation of tree biodiversity indices with AGC (Mg/ha)

Correlation coefficient (r)	AGC
Shannon(H)	0.04
Evenness (E)	-0.117
Simpson index	0.224
Richness(S)	0.305
Tree stem/ha	-0.209
Basal area	0.647**

Figures

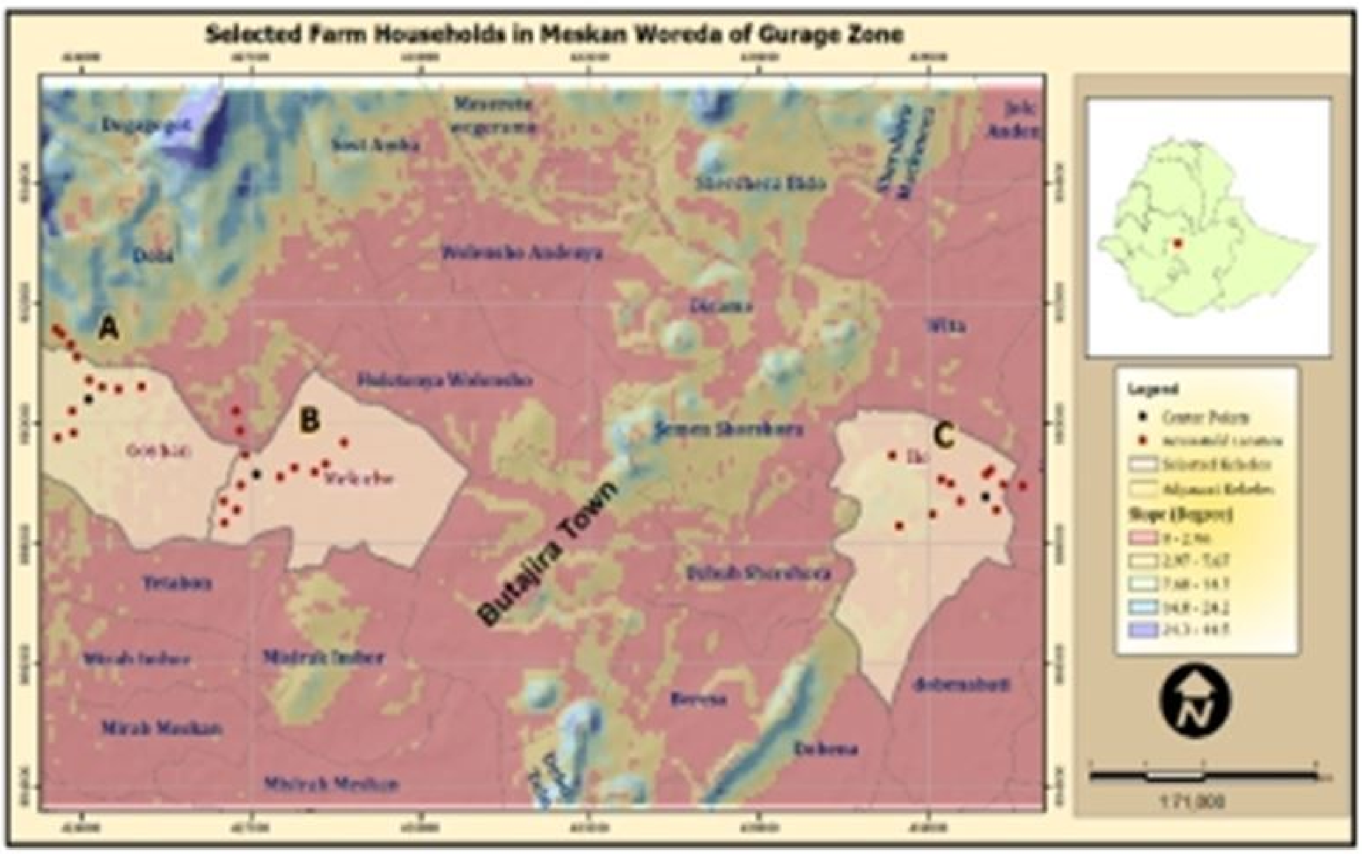

Figure 1

Map of the study area and location of households considered in the study. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

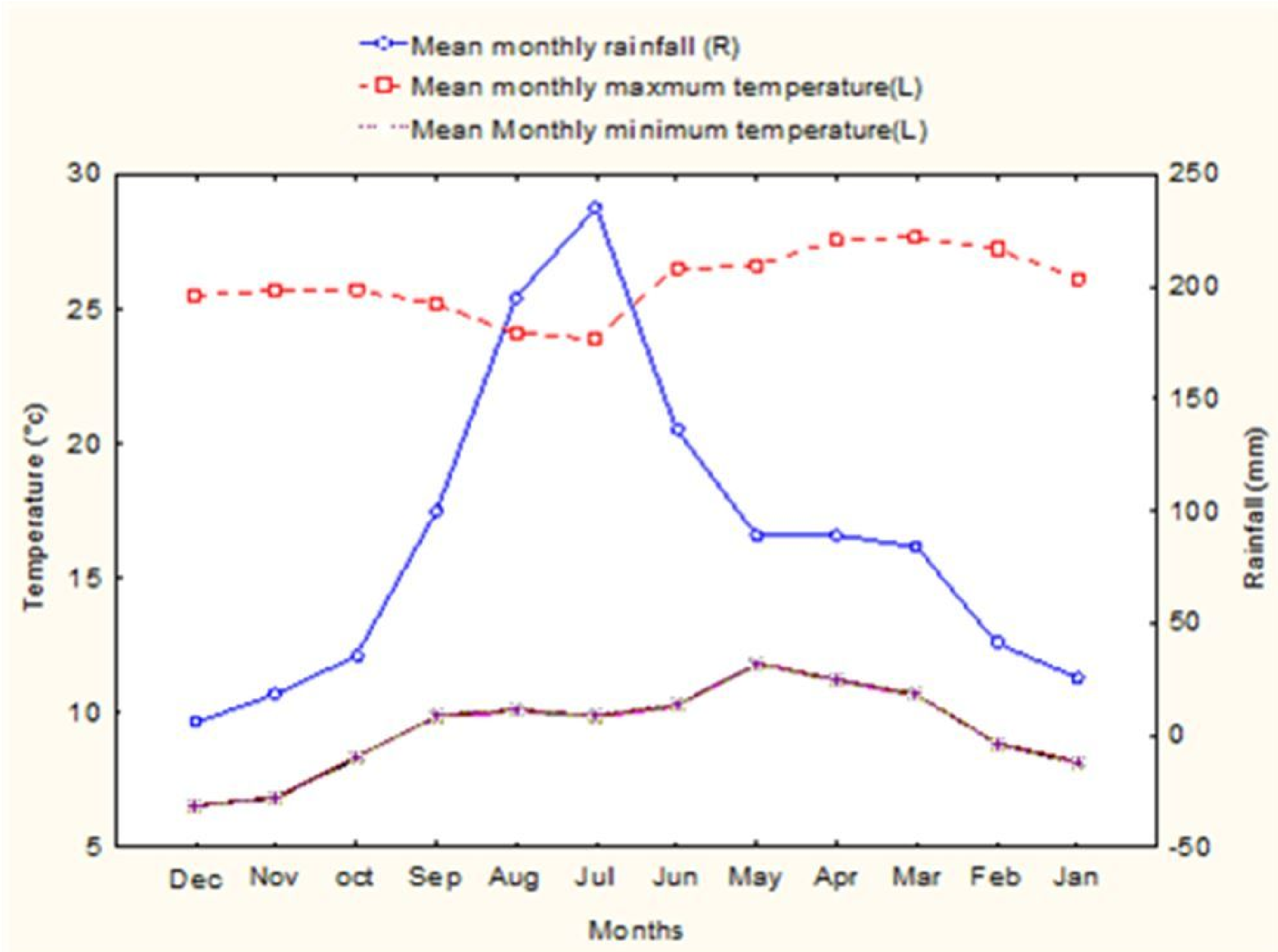

Figure 2

Climatic condition of the study area (Source: NMAE, 2014).