Aboveground carbon stock is related to land cover and woody species diversity in tropical ecosystems of Eastern Ethiopia

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Abstract

Background: Current theories on biodiversity-carbon sequestration relationship describe biodiversity as an important factor influencing carbon storage, either through complementarity effect or by mass ratio effect. So far, the expected form of biodiversity-carbon relationships in tropical ecosystems has not been known with certainty. Therefore, we explored the relationship between aboveground carbon stock and different biodiversity measurement indices (i.e., species richness, species diversity, species evenness, and functional diversity) in different land cover types of Eastern Ethiopia. A total of 48 plots were established using stratified random sampling. Vegetation parameters such as diameter at breast height, diameter at stump height, tree height, and species type were recorded.

Results: We found that the average aboveground carbon stock of the study area is 147.6 ± 17.2 t ha$^{-1}$ (mean, SE) across land cover types. Species richness, Shannon index, and functional diversity together explained 73.5%, 61.4%, 58.9%, and 52.0% of the variation in aboveground carbon storage in woodland, riparian forest, bushland, and farmland, respectively. Functional diversity was a significant predictor explaining the total aboveground carbon stocks (26.7%) across the land cover types. The effects of biodiversity on aboveground carbon storage were mediated by functional diversity and presence and dominance of species. This shows that both the selection effects and the niche complementarity are important for carbon storage. However, the impact of functional diversity effects (niche complementarity) was higher than that of functional dominance effects (selection effects).

Conclusions: Implementation of protected area-based ecosystem conservation practices in the country seems feasible to mitigate climate change and Reducing Emissions from Deforestation and Forest Degradation (REDD+) programme should emphasize on biodiversity conservation.

Keywords: Niche complementarity effect, Functional diversity, Selection effect, Species diversity, Species richness
Introduction

Global biodiversity is increasingly threatened by human domination of the natural ecosystem and its concomitant impacts that accelerate rates of biodiversity loss and homogenization through invasion (Sala et al. 2000). Loss of biodiversity might cause a significant change in CO₂ exchanges between the land and the atmosphere (Thomas 2013). The change raises fundamental questions such as “will biodiversity loss and variation alter basic ecosystem processes of carbon storage?” To address such questions, in the past 30 years, increasingly considerable attention has been given to in the determination of relationships between biodiversity and ecosystem functions. Although loss of biodiversity is relatively well studied, quantitative assessments of the association between biodiversity and its potential ecosystem function, particularly its role in carbon (C) storage, have not been adequately addressed (Thomas 2013; Harpole et al. 2016).

In terrestrial ecosystems, biodiversity influences both the magnitude (Reich et al. 2001; Tilman et al. 2014) and variability (Bai et al. 2004) of aboveground biomass. Aboveground biomass can significantly determine carbon storage potential of the ecosystem, which plays a significant role in balancing the global carbon budget (Mensah et al. 2016; Forrester et al. 2018). Current theories on biodiversity-carbon sequestration relationship describe biodiversity as an important factor influencing carbon storage, weather, and forest diversity effects which are driven by niche partitioning and facilitation (i.e. the complementarity effect) or by the selection of highly productive species such as the selection effect (i.e., the mass ratio effect) (Cardinale et al. 2012; Madrigal-González et al. 2016; Van Der Sande et al. 2017). The niche complementarity hypothesis states that diverse characteristics of species have a higher divergence of functional traits and can thus help to utilize resources better (Cardinale et al. 2012; Tilman et al. 2014; Yuan et al. 2018). The mass ratio hypothesis states that diversity can increase productivity through selection effects (Loreau and Hector 2001; Oram et al. 2017; Van Der Sande et al. 2017). Positive diversity-productivity relationships have been also found in low diversity mid-latitude (Forrester et al. 2018; Vanhellemont et al. 2018), due to a large canopy packing through complimentary canopy in higher diversity ecosystems (Jucker et al. 2016). Yet, the expected forms of biodiversity-carbon relationships in tropical ecosystems are not fully understood (Cardinale et al. 2012; Liang et al. 2016; Forrester et al. 2018). Thus, a better understanding of how biodversity affects carbon storage would help direct preservation, conservation, and restoration plans for exploited ecosystems.

Most studies that examined diversity-carbon storage relationships focused principally on species richness as a measure of biodiversity. In fact, biodiversity can be determined in different ways, as the number of species (species richness), the distribution of individuals over species (species evenness), or a combination of richness and evenness, as represented by Shannon index (Stirling and Wilsey 2001). Results of several studies led to the argument that evenness, Shannon index and species richness are different independent indices (Mason et al. 2005; Wilsey and Stirling 2007; MacDonald et al. 2017), and the recommendation that they be treated separately (Stirling and Wilsey 2001; Zhang et al. 2012a). Thus, evaluating the effects of different diversity metrics on carbon stock potential has been demonstrated to be rare (Zhang et al. 2012b; Forrester et al. 2018). The different metrics of diversity may have different predictive powers in different land cover types for predicting carbon storage potential. In this study, we tested the effect of different diversity metrics on aboveground carbon stocks. Ethiopia is recognized as a hotspot for biodiversity but is suffering from rapid and extensive loss of biodiversity (Myers et al. 2000; Goren et al. 2012; Di Marco et al. 2014). The demand of forest products is quite pronounced as more than 85% of the people living in rural areas that mostly rely on biodiversity for their basic needs such as cattle feed, fuelwood, food, and shelter. In spite of the increasing demand, Ethiopia has been able to maintain a considerable area of land for biodiversity conservation during the last decade. The rate of afforestation in the country is considered to be one of the highest among sub-Saharan countries and has played a role in maintaining biodiversity particularly forest cover and productivity. Despite efforts being exerted to conserve the increasing biodiversity, our knowledge on the role of biodiversity as dynamic C-pools in biogeochemical cycles and the mechanisms underlying the effects of diversity on carbon stock is largely unknown. This would pose challenges to policy development aimed at promoting, managing, or protecting biodiversity to safeguard the atmospheric environment from Greenhouse Gas (GHG) emissions, in addition to providing local people with reasonable means of livelihood. Therefore, it is necessary to understand the role of biodiversity in storing carbon, which is fundamental in quantifying its contribution to climate change mitigation since the quantified amount of carbon indicates the amount of carbon that can be offset (Ditt et al. 2010; Jabareen 2013; Felton and Gustafsson 2016). However, carbon stocks and woody species diversity in different land use types have not been assessed in Babile Elephant Sanctuary. Moreover, it is not clear how different measures of biodiversity are correlated with aboveground carbon stock. Do land use types show variations in aboveground carbon stock? What relationships do exist between different biodiversity measurement indices and aboveground carbon stock under different land use
types? Here, we explored the relationships between above-ground carbon stock and different biodiversity measurement indices (i.e., species richness, species diversity, species evenness, and functional diversity) in the different land cover types of Eastern Ethiopia.

**Materials and methods**

**Study site**

Babile Elephant Sanctuary (BES) is situated in the Somali-Masaai centre of endemism in Ethiopia. The sanctuary, which is 6892 km² in size, was established in 1970 to protect the only viable elephant population in the Horn of Africa. The sanctuary is located 560 km to the east of Addis Ababa (capital city of Ethiopia). Its geographical position is within latitudes of 08° 22′ 30″—09° 00′ 30″ N and longitudes of 42° 01′ 10″—43° 05′ 50″ E (Fig. 1) and has an elevation ranging between 850 and 1785 m above sea level. Topographically, it is predominantly characterized by flat to gentle slopes, comprising about 84% of the total sanctuary area while the remaining 16% consists of complex valleys and deep gorges. Four main drainage river valleys (Fafem, Dakata, Erer and Gobele) rise from Garamuleta-Gursum highlands, and these extend southwards through the sanctuary to join the Wabi Shebelle River Basin. Wide ranges of wildlife species inhabiting the sanctuary include the African elephant (*Loxodonta africana*), black-maned lion (*Panthera leo*), leopard (*P. pardus*), and Hamadryas baboon (*Papio hamadryads*). The sanctuary is also shelter for a range of antelopes, lesser and greater kudus, leopards, spotted hyenas, wild pigs, warthog, and a variety of reptiles and birds.

**Study area and site selection**

The study sites were selected using stratified purposive sampling. Four different land cover categories (i.e., treatments) were identified, namely, farmland, riparian forest, woodland, and bushland (Table 1). The description of the land cover classes was based on the standard classes defined by the US Geological Survey (Mohan et al. 2011), and land use land cover study conducted in the study area (Sintayehu and Kassaw 2019).

**Sampling and plot establishment**

A reconnaissance survey was carried out in order to have an impression of the site conditions and determine samples of farmland, riparian forest, woodland, and
bushland cover types. Plant species diversity, vegetation structure, and carbon stock potential of the study area in different land cover types were studied by using a stratified sampling method. First, the study area was stratified according to land cover type. In each land cover type, a total of four transect lines of 1000 m each, which were 300 m apart, were established systematically. In each transect, at an interval of 200 m, main plots of 10 m × 10 m for trees, 4 m × 4 m for shrub, and 1 m × 1 m for herbaceous land were established. Aboveground carbon was assessed for each nested sub-plot (Henry et al. 2011; Dabasso et al. 2014). The assessments were done for two consecutive wet and dry seasons from 2015 to 2017.

### Data collection

**Aboveground woody carbon assessment**

In the established sub-plots ($n = 20$ per land cover type per season), the woody plant diameters were measured using a diameter tape at breast height (i.e., 1.3 m above ground) (Ditt et al. 2010). Diameter measurement for trees and lianas was taken at breast height (1.3 m) using a calliper. For tree species that branched at breast height, the diameters were measured separately above the swelling, and the average measurements were recorded. For tree species that forked below 1.3 m, individual stem diameters were separately measured and treated as two trees (Abed and Stephens 2003). Tree species were recorded for all trees within the plots using scientific and local names. For trees that were difficult to identify, voucher specimens were brought to the Herbarium of Haramaya University for identification where the voucher specimens of plant species were deposited.

**Aboveground herbaceous carbon assessment**

Herbaceous materials within 1 m² were then clipped at 1 cm stubble height. The clipped materials, together with litters, were put in to paper bags, and their fresh weights were recorded. The aboveground materials of herbaceous plants were oven-dried at 80°C for 48 h.

### Data analysis

Four indices of plant diversity were calculated per plot, namely, species richness, species diversity, species evenness, and functional diversity. Species richness is the total number of species present within a plot in each land cover types. Functional diversity was calculated at the plot level, following the methods of Paquette and Messier (Paquette and Messier 2011).

Functional traits that are related to carbon storage were considered to assess functional diversity (Mensah et al. 2016). Carbon storage is strongly dependent on wood density, diameter of the plant, and maximum plant height. Thus, for functional diversity, we calculated the dispersion for wood density, maximum DBH, and maximum height based on the trait value of the species present at each plot (Mensah et al. 2016). Shannon diversity index ($H'$) was calculated for each plot, which has been used to estimate plant species diversity as:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

where $p_i$ is the proportion of species $i$, and $S$ is the number of species (Hill, 1973). Pielou’s index was used to estimate plant species evenness (Hill 2007), which is most widely used in ecology (Zhang et al. 2012a):

$$J' = \frac{H'}{\ln S}$$

where $H'$ represents the Shannon diversity index, and $S$ is the total number of species observed. Biodiversity metrics were calculated using package vegan of R v3.2.0.

**Aboveground carbon stocks**

Aboveground carbon (AGC) stocks were calculated for all land cover type by summing the values for the nested plots along each land cover type, and dividing by the total sampled area, in ha.

**Aboveground carbon assessment of woody species**

The diameter at breast height (DBH) (1.3 m above the ground) of all the trees within 10 m × 10 m nested sub-plots and basal diameters (BD) of all shrubs within the 4 m × 4 m nested sub-plots was taken using a flexible measuring tape. Both DCH and BD were recorded, and carbon estimates within each plant were done using allometric equations as described by Henry et al. (2011) as follows:

- Trees: $Y = 0.1975 \times (\text{DBH}^{1.1859})$
- Shrubs: $Y = 0.1936 \times (\text{BD}^{1.1654})$

where $Y$ is the fresh weight of trees/shrub biomass (kg).

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**Table 1** The description of land cover (LC) types used in BES

| LC types          | General description                                                                 |
|-------------------|---------------------------------------------------------------------------------------|
| Farmland          | Area of land ploughed or prepared for growing crops (i.e., both areas identifiable under crop agriculture and land under preparation). |
| Bushland          | Area of land covered with shrubs, bush, and small trees in which multiple stems and branches are produced from the base of the main stem. |
| Woodland          | Area of land dominated by Acacia species with mean height of above 5 m and the canopy cover ranges from 10 to 40% for open woodland and above 40. |
| Riparian forest   | A type of forest found along the four major perennial rivers. The vegetation is usually evergreen (due to continuous water supply from the rivers). |

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The results of allometric equation provide fresh biomass estimates. In order to measure dry biomass, the results were multiplied by 60%, and the aboveground carbon content was taken as 50% of the dry biomass weight (Henry et al. 2011; Saatchi et al. 2011). Aboveground carbon estimates within nested sub-plots were converted to carbon in tons per hectare (1 ton = 1000 kg, 1 ha = 10,000 m²).

**Aboveground carbon assessment of herbaceous species**

Herbaceous carbon contents were calculated as 50% of oven-dried herbaceous biomass. The results were recorded in a prepared data sheet. Sample results were then converted into carbon tons per hectare (1 ton = 1,000,000 g) (Henry et al. 2011; Dabasso et al. 2014). Pearson statistical tests were performed to test correlations between aboveground carbon stocks and biodiversity for different land cover types. We used ANOVA using R's “car” package to test the effects of land cover types on total AGC stocks in different seasons. To estimate the variation explained by each biodiversity measurement indices, adjusted $R^2$ (Bunker et al. 2005) was used. We performed these analyses using the vegan package in R. All analyses were carried out in R v3.2.2 (R Development Core Team, 2015).

**Results**

**Vegetation structure and floristic composition**

A total of 137 plant species were identified and measured over 48 plots of the survey area belonging to 85 genera and 41 families (Appendix in Table 5). The mean stand density was 419 ± 28 stems ha⁻¹. The number of stands ranged from 24 to 2458 stems ha⁻¹. The mean diameter was 1.27 ± 0.21 m, with the majority of trees being found within the smaller diameter classes (Table 2). The mean basal area was 14.34 ± 0.52 m² ha⁻¹, with a minimum of 10.48 and maximum of 18.8 m² ha⁻¹ across the plots.

**Diversity of plant species**

Species richness in the study area was significantly different among land cover types ($F = 4.65$, $P < 0.01$), as woodland had higher species richness ($n = 48$; Table 2). Species diversity as measured by the Shannon index ($H'$) ranged from 2.62 to 0.78 (Table 2) and was found to be high in the woodland ($H' = 2.62$) and riparian forest ($H' = 2.50$), and low ($H' = 0.78$) for farmland where the high and low $H'$ values were significantly different ($P < 0.05$). Species evenness was not significantly different between land cover types ($F = 0.61$, $P = 0.55$). The functional diversity ranged from 0.80 to 0.92 (Table 2).

**Aboveground carbon stocks**

The total aboveground carbon stock of the area in different land cover types ranged between 7.14 and 71.16 t ha⁻¹ (Table 3). The total carbon stocks from the different land use types showed a statistically significant difference ($P < 0.001$) (Table 3). The largest aboveground C stocks were found for the riparian forest (71.16 ± 0.91 t ha⁻¹), followed by woodland (43.09 ± 0.42 t ha⁻¹), whereas the smallest aboveground C stocks were measured for the farmland (7.14 ± 0.38 t ha⁻¹).

**Relationship between diversity and aboveground carbon stocks**

Species richness, Shannon index ($H'$), and functional diversity together explained 73.5, 61.4, 58.5, and 51.6% of the variations in the aboveground carbon storage in woodland, riparian forest, bushland, and farmland, respectively, and the contribution to carbon storage variation differed among the land cover types (Fig. 2).

Functional diversity explained most of the variations in the aboveground carbon storage on riparian forest (42.1%) and woodland (28.1%); more specifically, we found that the more DBH and Hmax of a plot, the greater the increase in carbon storage. Species diversity explained most of the tree carbon storage variation (22.1%) in farmland. Another important source of variation was the interaction between species diversity and functional diversity which explained 11% of the carbon storage variation in riparian forest, 6% in bushland, and 4% in woodland. The relationships between species richness and total aboveground carbon stock were significant for riparian forest enclosures ($r = -0.15$, $p < 0.05$). The relationships between species diversity (Shannon) and total aboveground carbon stock were also significant for bushland ($r = 0.39$, $p < 0.05$) and farmland ($r = 0.52$, $p < 0.05$). Functional diversity showed

| Land cover type       | n (plot) | $H'$ | $S$ | $J$ | DBH (m) Mean | Min. | Max. | Height (m) Mean | Min. | Max. | Density (stems ha⁻¹) |
|-----------------------|---------|------|-----|-----|-----------|------|------|-----------------|------|------|---------------------|
| Riparian forest       | 12      | 2.50 | 47  | 0.92| 1.87      | 1.87 | 2.52 | 4.31            | 1.65 | 5.42 | 145.6               |
| Woodland              | 12      | 2.62 | 78  | 0.90| 1.05      | 0.65 | 1.96 | 2.06            | 1.48 | 2.58 | 524.5               |
| Bushland              | 12      | 1.86 | 45  | 0.84| 0.18      | 0.04 | 0.98 | 1.28            | 0.74 | 2.14 | 916.4               |
| Farmland              | 12      | 0.78 | 9   | 0.80| 1.56      | 0.78 | 3.22 | 1.78            | 1.52 | 2.21 | 37.27               |

$J$ species evenness, $H'$ species diversity, $S$ species richness, DBH diameter at breast height
significant relation with total carbon stock, for riparian forest ($r = 0.81$, $p < 0.001$), for woodland ($r = 0.58$, $p < 0.01$), and bushland ($r = 0.45$, $p < 0.05$) (Table 4).

**Discussion**

The results of the study revealed that the aboveground carbon stocks were positively correlated with biodiversity, which confirms the positive association commonly observed between diversity and biomass in different experimental studies (Cardinale et al. 2006, 2007, 2011; Duffy et al. 2007; Delgado-Baquerizo et al. 2016), as well as in recent in situ forestry studies (Wang et al. 2009; Saatchi et al. 2011; Finegan et al. 2015; Delgado-Baquerizo et al. 2016). Thus, the results support the positive biodiversity-ecosystem functioning hypothesis. This synergistic association suggests that conservation of biodiversity can lead to enhanced quantities of carbon stored in a given area.

The results of the aboveground carbon storage in natural ecosystems (riparian forest, woodland, and bushland) were mainly explained by functional diversity incorporating wood density, maximum diameter, and maximum height traits in natural habitat and carbon stocks. However, we found no association between carbon storage and species richness in the natural ecosystems. Similarly, reports by Zhang et al. (2012a) indicated that no significant relationship was found between aboveground carbon storage and species richness in naturally regenerating conifer stands in China. Species richness only mattered in agricultural land, where increasing the number of species also increased carbon storage. This association was expected because in agricultural land crops, there are planted according to different species functions, including provision of shade, control of wind erosion, and nutrient recycling ability (Richards et al. 2010). Lack of significant correlation between carbon storage and species richness in the natural ecosystems indicates that the ecosystems may have reached saturation in species richness, an effect that can be found in high species richness treatments in experimental grasslands (Cardinale et al. 2011). In those systems, < 15 species are needed to reach the highest values of plant productivity (Loreau and Hector 2001; Van Der Sande et al. 2017). Saturation between carbon storage and species number can differ among sites and is determined by the niche overlap among species (Cardinale et al. 2007).

The study shows a clear correlation between functional diversity and total carbon stock. The significant positive correlation between aboveground carbon stocks potential and a functional diversity consisting of wood density and maximum diameter traits might be due to complementarity effect, in which a diverse array of species has a greater divergence of functional traits and can thus better utilize limiting resources, thus increasing total ecosystem functioning, than a less diverse community. The complementarity effect is the increase in relative productivity among species in a mixture compared with the productivity of the species grown in monocultures due to positive interactions among species (i.e., facilitation and partitioning of resources) (e.g., Reich et al. 2001; Tilman et al. 2014). Positive diversity-productivity relationships have been found in low diversity mid-latitude forests, potentially due to increased canopy packing through complimentary canopy in higher diversity areas. Studies have showed that plant diversity enhances biomass production, with niche partitioning and positive interactions among species allowing diverse communities to utilize resources more effectively.

We chose wood density, maximum diameter at breast height (DBH), and maximum height as functional traits

**Table 3** Carbon stocks in the different land cover (LC) types of BES

| LC types        | AG herbaceous carbon (t ha$^{-1}$) | AG woody carbon (t ha$^{-1}$) | Total carbon (t ha$^{-1}$) |
|-----------------|-----------------------------------|-------------------------------|-----------------------------|
| Riparian forest | 15.12 ± 0.25a                     | 56.04 ± 0.71a**              | 71.16 ± 0.91a*             |
| Woodland        | 26.86 ± 0.03a                     | 16.23 ± 0.41b                | 43.09 ± 0.42b              |
| Bushland        | 31.41 ± 0.11a                     | 8.81 ± 0.27b                 | 40.22 ± 0.35b              |
| Farmland        | 2.45 ± 0.36a                      | 4.68 ± 0.39b                 | 7.14 ± 0.38c               |

*a* Means with the same letters in the same column are not significantly different at $P < 0.05$

AG Above-ground; the same letters in the same column are not significantly different at $P < 0.05$

*P < 0.05, **P < 0.01

![Fig. 2 Proportion of aboveground carbon storage variation explained by different land cover types in BES](image-url)
related to tree carbon storage (Baker et al. 2004; Jucker et al. 2016). Martinez-Garza (2013) showed that functional traits have been proposed as an improved way to understand forest dynamics in hyper diverse tropical forests because they are considered the redundancy in function of species. This function can cluster species based on their resource use. To link functional traits to a specific function, we need to select traits that are related to carbon storage function of the ecosystem. Wood density partly determines aboveground biomass (Day et al. 2018) and correlates with growth rates and tree mortality (Madrigal-González et al. 2016), a high wood density being associated with long-lived and slowly growing plant species. Similar with the results of previous studies, we found that both basal area and density of woody species are constituents of biomass estimates (Cruz et al. 2016). Martinez-Garza (2013) showed that functional diversity and species richness, functional diversity, species dominance, and functional dominance in different land cover types in Eastern Ethiopia

| Biodiversity              | Carbon storage in different land cover type |
|---------------------------|--------------------------------------------|
|                           | Riparian forest | Woodland | Bushland | Farmland |
| Species richness          | 0.23            | 0.45     | 0.34     | 0.54     |
| Functional diversity      | 0.58**          | 0.45*    | 0.34     |          |
| Species evenness          | 0.51            | 0.13     | 0.44     |          |
| Shannon index * functional diversity | 0.34           | 0.28     | 0.33     | 0.14     |

Table 4 Pearson correlations (r) and generalized linear mixed models to test the relationships between carbon storage with species richness, functional diversity, species dominance, and functional dominance in different land cover types in Eastern Ethiopia

Conclusions

The findings of this study have demonstrated that it is not exclusively that the selection and the niche complementarily effects influence carbon stock. Rather, the results have revealed that the influences were significantly attributable to functional diversity. However, the results require to be substantiated and validated through further studies in similar ecosystems. Therefore, the results of our study support stronger complementary effects that might be due to complementary light-use efficiency of woody plant growth in the understory layer. The findings also instigate that conservation efforts focused on protected area-based biodiversity conservation with ecosystem networks that may benefit both functional biodiversity and ecosystem services linked to carbon storage, like climate change mitigation. In this study, we have estimated aboveground carbon stocks as a case study of tropical deciduous woodland ecosystems under diverse land cover change, taking into considerations spatial and temporal heterogeneity of the ecosystem. The variation in carbon storage with land cover types affirms the need to examine asymmetric variation of environmental resource in the measurement of ecosystem carbon stocks. The results have also revealed that, compared to the cultivated land, natural ecosystems stored substantial amounts of carbon. The results of this study might also lead to initiation of a large-scale study in the Ethiopia deciduous woodland ecosystems on aboveground carbon stocks stored in soils and vegetation to analyze the relationship between structural and functional biodiversity and ecosystem services linked to carbon storage for better planning of ecosystem conservation and management.
### Table 5 List of plant species identified in the study area

| No. | Scientific name       | Family     | Habit       |
|-----|-----------------------|------------|-------------|
| 1   | Abutilon bidentatum   | Malvaceae  | Herb        |
| 2   | Acacia albida         | Fabaceae   | Tree        |
| 3   | Acacia brevispica     | Fabaceae   | Shrub/Tree  |
| 4   | Acacia bussei         | Fabaceae   | Tree        |
| 5   | Acacia ebraica        | Fabaceae   | Tree        |
| 6   | Acacia mellifera      | Fabaceae   | Shrub/Tree  |
| 7   | Acacia nilotica       | Fabaceae   | Shrub       |
| 8   | Acacia oerfota        | Fabaceae   | Shrub       |
| 9   | Acacia robusta        | Fabaceae   | Tree        |
| 10  | Acacia senegal        | Fabaceae   | Shrub       |
| 11  | Acacia seyal          | Fabaceae   | Tree        |
| 12  | Acacia tortilis       | Fabaceae   | Tree        |
| 13  | Acalypha fruticosula  | Euphorbiaceae | Shrub   |
| 14  | Achyranthes aspera    | Amaranthaceae | Herb |
| 15  | Acanthastera schimperi| Apocynaceae | Shrub/Tree |
| 16  | Agava sisalana        | Agavaceae  | Shrub       |
| 17  | Allophyus rubifolius  | Sapindaceae | Shrub   |
| 18  | Aloe pirottae         | Asphodelaceae | Shrub |
| 19  | Asparagus leptocladodius| Asparagaceae | Shrub   |
| 20  | Balanites aegyptica   | Balanitaceae | Tree |
| 21  | Balanites glabra      | Balanitaceae | Tree |
| 22  | Bankia eranthemoides  | Acanthaceae | Shrub       |
| 23  | Bankia parviflora     | Acanthaceae | Shrub       |
| 24  | Berchemia discolor    | Rhaminaceae | Tree        |
| 25  | Blephas edulis        | Acanthaceae | Herb        |
| 26  | Blephas maderaspatensis| Acanthaceae | Herb     |
| 27  | Boscia minimifolia    | Capparidaceae | Tree |
| 28  | Boswellia neglecta    | Burceraceae | Shrub       |
| 29  | Buckollia volubilis   | Asclepiadaceae | Climber |
| 30  | Calotropis procera    | Asclepiadaceae | Shrub  |
| 31  | Canthium setiferum    | Rubiaceae   | Shrub       |
| 32  | Capparis fascicularis | Capparidaceae | Climber |
| 33  | Capparis sepiaria     | Capparidaceae | Shrub  |
| 34  | Capparis tortososa    | Capparidaceae | Shrub  |
| 35  | Carissa spinorum      | Apocynaceae | Shrub       |
| 36  | Cerchus ciliaris      | Poaceae     | Grass       |
| 37  | Chloris pycnothrix    | Poaceae     | Grass       |
| 38  | Combretum molle       | Combretaceae | Tree     |
| 39  | Commelina stephaniniana| Commelinaceae | Herb |
| 40  | Commicarpus plumagineus| Nyctaginaceae | Climber |
| 41  | Commicarpus sinatus   | Nyctaginaceae | Climber |
| 42  | Commiphora erythræa   | Burceraceae | Tree        |
| 43  | Commiphora schimperi  | Burceraceae | Tree        |
| 44  | Corchorus tridens     | Tiliaceae   | Herb        |
| 45  | Corchorus trifolius    | Tiliaceae   | Climber     |
| 46  | Cordia gharaf         | Boraginaceae | Tree       |
| 47  | Cordia monoica        | Boraginaceae | Tree       |
| 48  | Cordia ovale          | Boraginaceae | Tree       |
| 49  | Crabbea velutina      | Acanthaceae | Herb        |
| 50  | Crinum abyssinicum    | Amaryllidaceae | Herb |
| 51  | Crotalaria quartiniana| Fabaceae    | Shrub       |
| 52  | Cryptostegia grandiflora| Asclepiadaceae | Climber |
| 53  | Dichrostachys cinerea | Fabaceae    | Tree        |
| 54  | Dichoma tormentosa    | Asteraceae  | Herb        |
| 55  | Dodonaea angustifolia  | Sapindaceae | Shrub       |
| 56  | Dolichos tilobus      | Fabaceae    | Herb        |
| 57  | Enteropogon macrostachyus| Poaceae     | Grass       |
| 58  | Euclera schimperi     | Ebenaceae   | Shrub       |
| 59  | Euphoria abyssinica   | Euphorbiaceae | Tree  |
| 60  | Euphoria burgeri      | Euphorbiaceae | Shrub |
| 61  | Euphoria cryptospinosa| Euphorbiaceae | Shrub |
| 62  | Euphoria polyacanthra | Euphorbiaceae | Shrub |
| 63  | Ficus vallis-choudae  | Moraceae    | Tree        |
| 64  | Ficus vasta           | Moraceae    | Tree        |
| 65  | Fluegea virosa        | Euphorbiaceae | Herb  |
| 66  | Grewia bicolor        | Tiliaceae   | Shrub       |
| 67  | Grewia erythraea      | Tiliaceae   | Shrub       |
| 68  | Grewia ferruginea     | Tiliaceae   | Shrub       |
| 69  | Grewia flavescens     | Tiliaceae   | Shrub       |
| 70  | Grewia kokothamnos    | Tiliaceae   | Shrub       |
| 71  | Grewia schwarifurthis | Tiliaceae   | Shrub       |
| 72  | Grewia tenax          | Tiliaceae   | Shrub       |
| 73  | Grewia vilosa         | Tiliaceae   | Shrub       |
| 74  | Gutenbergia rueppelli | Astereaceae | Herb        |
| 75  | Hibiscus dogoleus     | Malvaceae   | Herb        |
| 76  | Hibiscus ludwigii     | Malvaceae   | Shrub       |
| 77  | Hibiscus micrantus    | Malvaceae   | Shrub       |
| 78  | Hibiscus ovalifolius  | Malvaceae   | Shrub       |
| 79  | Indigofera brevicalyx | Fabaceae    | Herb        |
| 80  | Indigofera caerulea   | Fabaceae    | Herb        |
| 81  | Indigofera hochstetteri| Fabaceae    | Herb        |
| 82  | Indigofera parviflora | Fabaceae    | Herb        |
| 83  | Ipomea hochstetteri   | Convolvulaceae | Herb  |
| 84  | Justicia schimperi    | Acanthaceae | Shrub       |
| 85  | Justicia dicipiteroides| Acanthaceae | Herb       |
| 86  | Justicia flavus       | Acanthaceae | Herb       |
Table 5 List of plant species identified in the study area (Continued)

| No. | Scientific name       | Family       | Habit          |
|-----|-----------------------|--------------|----------------|
| 87  | Kleinia odora         | Asteraceae   | Shrub          |
| 88  | Kleinia squarrosa     | Asteraceae   | Shrub          |
| 89  | Kohanaia caespitosa   | Rubiaceae    | Herb           |
| 90  | Lankea triphylla      | Anacardiaceae| Shrub          |
| 91  | Lantana camara        | Verbenaceae  | Shrub          |
| 92  | Lantana viburnoides   | Verbenaceae  | Shrub          |
| 93  | Leucas abyssinica     | Lamiaceae    | Shrub          |
| 94  | Leucas martincensis   | Lamiaceae    | Herb           |
| 95  | Melinis repens        | Poaceae      | Grass          |
| 96  | Ocimum gratissimum    | Lamiaceae    | Shrub          |
| 97  | Ocimum lamifolium     | Lamiaceae    | Herb           |
| 98  | Oncoba spinosa        | Flacouriaceae| Tree           |
| 99  | Opunia ficus-indica   | Cactaceae    | Tree           |
| 100 | Opunia stricta        | Cactaceae    | Shrub          |
| 101 | Ozocra insignis       | Anacardiaceae| Tree           |
| 102 | Panicum monticolum    | Poaceae      | Grass          |
| 103 | Pappea capensis       | Sapindaceae  | Tree           |
| 104 | Pavetta gardenifolia  | Rubiaceae    | Shrub          |
| 105 | Pentaninium somalensis| Asclepiadaceae| Climber     |
| 106 | Plectranthus barbatus  | Lamiaceae    | Herb           |
| 107 | Plectranthus cylindracus| Lamiaceae    | Herb          |
| 108 | Plectranthus puberulentus| Lamiaceae    | Shrub         |
| 109 | Plectranthus rupestrus | Lamiaceae    | Herb          |
| 110 | Plicasepalus curviflorus| Loranthaceae| Epiphyte      |
| 111 | Plumbago zeylanica    | Plumbaginaceae| Herb        |
| 112 | Premna oligostrica    | Lamiaceae    | Shrub          |
| 113 | Prospis juliflora     | Fabaceae     | Shrub          |
| 114 | Rhus natalensis       | Anacardiaceae| Shrub         |
| 115 | Salvador persica      | Salvadoraceae| Tree           |
| 116 | Sarcostema viminalis   | Asclepiadaceae| Climber    |
| 117 | Senna obtusifolia     | Fabaceae     | Shrub          |
| 118 | Senna singueana       | Fabaceae     | Shrub          |
| 119 | Setaria verticillata  | Poaceae      | grass          |
| 120 | Solanecio angulatus   | Asteraceae   | Climber        |
| 121 | Solanum incanum       | Solanaceae   | Herb           |
| 122 | Solanum nigrum        | Solanaceae   | Herb           |
| 123 | Steganotaenia aralacea| Apiaceae     | Tree           |
| 124 | Sterculia africana    | Sterculiaceae| Tree           |
| 125 | Tamarindus indica     | Fabaceae     | Tree           |
| 126 | Terminalia brownii    | Combretaceae | Tree           |
| 127 | Trichilia emetica     | Meliaceae    | Tree           |
| 128 | Triumfetta heterocarpa | Tiliaceae    | Shrub          |
| 129 | Tylosema fassoglenis  | Fabaceae     | Climber        |
| 130 | Vepris glomerata      | Rutaceae     | Shrub          |
| 131 | Vernonia cinerascens  | Asteraeceae  | Shrub          |
| 132 | Ximenia caffra        | Olaceae      | Shrub          |
| 133 | Zanthoxylum chalybeum  | Rutaceae     | Tree           |
| 134 | Zinia pergiana        | Asteraeceae  | Herb           |
| 135 | Zoisphus spina-christi| Phamaceae    | Tree           |
| 136 | Zania glochidiata     | Fabaceae     | Herb           |

Abbreviations
BES: Babile Elephant Sanctuary; DBH: Diameter at breast height; BD: Basal diameter; AGC: Aboveground carbon

Acknowledgements
We sincerely thank Haramaya University for funding this research.

Authors’ contributions
SWD, AB, and ND initiated the work, and writing and revising the manuscript. The authors read and approved the final manuscript.

Funding
This study was funded by Haramaya University.

Availability of data and materials
The authors declare that all data and materials used in the publication will be available online.

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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Received: 11 April 2019 Accepted: 25 May 2020
Published online: 14 July 2020

References
Abed T., Stephens N.C. (2003) Calculating volumes for stands greater than three hectares. In Tree Measurement Manual for Farm Foresters. 2nd edn. Ed M. Parsons. Canberra: National Forest Inventory, Bureau of Rural Sciences, Commonwealth of Australia. 43–52.
Bai Y, Han X, Wu J, Chen Z, Li L (2004) Ecosystem stability and compensatory effects in the Inner Mongolia grassland. Nature 44:1992–1995
Baker T VR, Phillips OL, Malhi N, Almeida S, Arroyo L, Anthony Difiorek A et al (2004) Variation in wood density determines spatial patterns in Amazonian forest biomass. Glob Chang Biol 10:545–562
Bunker DE, Declerck F, Bradford JC, Colwell RK, Perfecto I, Phillips OL, Sankaran M, Parson. Canberra: National Forest Inventory, Bureau of Rural Sciences, Commonwealth of Australia. 43–52.
Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P et al (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67
