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Carbon stock and woody species diversity patterns in church forests along church age gradient in Addis Ababa, Ethiopia

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Abstract

Most of the Ethiopian Orthodox Churches comprise natural and planted forests and trees on their premises. A study was conducted to investigate carbon stock and woody species diversity patterns along the church age gradient in Addis Ababa city. We hypothesized that the carbon stock would relate to the church age gradient. Thus, the study was conducted in forests belonging to churches that were selected in a stratified random sampling from four age categories with the year of establishments ranging from 1897 to 1993. Counting of all the woody species and DBH and height measurement of all individuals with DBH of 5 cm and above was carried out. Carbon stock and different diversity indices were computed, and the relationships between church age and tree parameters were evaluated. Results showed that the forests were characteristically small (0.6 ± 0.57 ha), and the tree species with the highest total carbon stock were *Juniperus procera, Eucalyptus globulus* and *E. camaldulensis.* The mean amount of carbon stock contained in each church forest was 156 ± 92 t ha-1. A total of 50 indigenous and 40 exotic woody species were identified. A statistically significant difference ($p < 0.05$) among the four Strata was revealed for the carbon stock of native trees. Correlation analysis also revealed a significant positive relationship between church age and native trees' carbon stock. We conclude that the church forests have a very important role in carbon sequestration and biodiversity conservation, and thus scaling up the long-term maintenance and management of such small-sized forests in urban green spaces is vital.

Keywords Biodiversity conservation · Climate change mitigation · Diversity indices · Urban forest

Introduction

Environmental problems are a widespread concern because of the threats and risks related to global weather patterns, global warming, natural disaster, and the loss of biodiversity (Freestone and Streck 2009). The loss of biodiversity and the high rate of species extinction are caused mainly by human activities (Sisk et al. 1994; Betemariam 2011; Mebrat and Gashaw 2013; Sisk et al. 1994). The loss of biodiversity, in turn, is one of the main threats to the world's forests because it is essential for ecosystem function and stability (Tilman 2000). Therefore, Maintenance of the biological diversity and the ecosystem carbon balance is important (Midgley et al. 2010; Midgley and Bond 2015). To this effect, a comprehensive understanding of forest structural diversity and carbon sequestration capacity within the forest ecosystems is essential (Bosworth et al. 2008). In this discourse, the urban green areas and specifically urban forests role deserve attention.

Urban green areas represent a necessary feature of urban landscapes (Momm-Schult et al. 2013). They provide ecosystem services, either through local climate regulation (Jim and Chen 2008), carbon sequestration (Strohbach and Haase 2012) or reduction of stormwater runoff (Ellis 2013) and can contain relatively high levels of biodiversity (Alvey 2006). Urban green spaces play essential roles in making cities more resilient to the effects of climate change (McPhearson et al. 2015). However, they must have proper design and maintenance for an increased role as carbon sinks and reduced carbon footprint (Strohbach et al. 2012).

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Urban forests comprise tree stands as well as individual trees including all tree-based vegetation in and near urban areas, parks and gardens, nature areas, street and square trees, plantations, woodlots, botanical gardens and trees in residential areas, office compounds, schools, churches, mosques and cemeteries (Alvey 2006; Bentsen et al. 2010; Konijnendijk et al. 2006). In Addis Ababa city, church forests are one of the dominant urban forest types and often comprise patchy remnants of old-aged forests (Wassie et al. 2005). The Ethiopian Orthodox Tewahedo Church has a long history of planting, protecting and preserving old-aged trees in its premises (Tilahun et al. 2015; Aerts et al. 2016; Tilahun et al. 2015), and these areas have in-situ and ex-situ biodiversity conservation values.

Therefore, the role played by the Church in maintaining and managing forests and trees in urban areas is paramount, and understanding biodiversity conservation, climate change mitigation and urban greening contributions of the church forest is important (Tura et al. 2013). However, the potential of church forests for maintenance of woody species diversity and carbon sequestration and climate change mitigation in cities of Ethiopia were not systematically studied.

We hypothesized that the carbon stock available in a unit of land could be related partly to the chrono-sequence of church establishment as both the maintenance of natural forests and the initial planting of trees would have varied with the age of the churches. We also hypothesized that species composition would vary randomly as a church could continue to diversify its forest and plant even after its establishment. Species composition could also depend on the size of the church forest and can be under the influence of the socioeconomic contexts under the different Ethiopian government eras.

There were as such institutional changes in forest property rights regimes during regime changes (Bekele 2003).. Milestone policy changes that happened during the different governments with great implication to forest resources conservation and development include the 1965 Imperial Forest Law, the 1975 Land Reform, the 1980 Forest Law, the 1994 Ethiopian Forestry Action Programme (EFAP), the 1994 Forest Law, the 2001 Rural Development Policy and Strategy, and the 2007 Forest Policy (Ayana et al. 2013). Therefore, these policy and institutional changes coupled with technological and overall societal changes could have affected what was happening in church forests and could be reflected in differences in forest composition.

Thus, the general objective of the study was to characterize woody species diversity and estimate the carbon stock potential of selected church forests in Addis Ababa along the age gradient of the churches. The specific objectives were to (1) estimate carbon stock in living above and below-ground biomass of woody species, (2) evaluate woody species composition and diversity of church forests, and (3) determine the relation between carbon stock, church age, density, basal area and woody species composition (proportion of exotic tree species) in Addis Ababa church forests established under four government eras (age strata).

Materials and methods

Description the study area

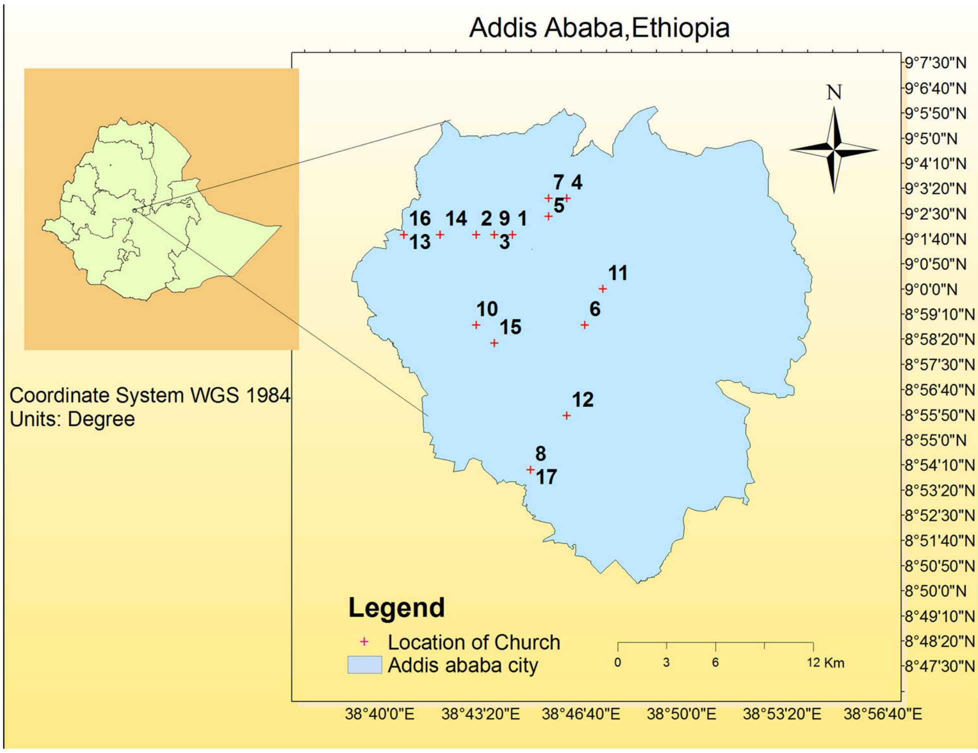
The study was carried out in the city of Addis Ababa, Ethiopia. The altitude of the study sites ranges between 2100 to 2900 m above sea level with geographical location of 8049′ 55” N to 905′53”N and 38,038′16″ E to 38,054′19″ E (Fig. 1).

The city covers 540 km^2, and the highest peak is Entoto whereas the lowest part is the Akaki plane. The upper part of the city is characterized by steep slopes with high mountains, flat-topped plateau while the lower part by less steep. The natural forest vegetation type in Addis Ababa belongs to the Afromontane undifferentiated forest and grassland complex (Friis et al. 2010). The average annual rainfall and temperature of Addis Ababa are 1114 mm and 17 °C, respectively (Fig. 2).

Sampling of church forests

Addis Ababa city has several small-sized forests that belong to the Ethiopian Orthodox Churches.They were established in the different government eras beginning from over more than a century ago. Stratified random sampling was conducted based on a list of churches in the city obtained from Addis Ababa Diocese (DIOCESE 2001), which recorded 141 churches. Out of this, 71 churches that had age information in the document were selected. We defined Church forest as all remnant and non-forest patches including patches of natural and planted forest, planting along sidewalks or as live fences, and scattered trees in open space that was the property of the specific Church. The selected churches were divided into four strata based on the years of establishment. Strata I comprises churches established in the Pre-Hailesellasie era (1897–1928) with age of 88 and above; Strata II comprises churches established in the Emperor Hailesellasie era (1930–1974) with age between 48 and 88 years; Strata III comprises churches established in the Dergue regime (1974–1991) with age between 28 and 48 years; and Strata IV comprises churches established in the Ethiopian Peoples Revolutionary Democratic Front (EPRDF) regime (from 1991 to date) with age below 28 years. The number of churches in each stratum was 24, 17, 14 and16, respectively, and a total of 6, 4, 4 and 4 churches, respectively, representing 25% of the churches in each age class were selected randomly. Because the data obtained from one of the churches in Strata IV, Debre Genet Furi Enqu Kidus Gebreal, was excluded from the analysis since the data from this church was an obvious outlier owing to removal of trees for construction on the site (Table 1).

Fig. 1 Map of the sampled seventeen church locations in Addis Ababa city
1 = Dagmawi Debre Libanos Debre Amen Teklehaymanot, 2 = Debre Gelila Amanueal, 3 = Debre Negodgwad Kidus Yehuwans, 4 = Genete Eyesus, 5 = Menbere Liaul Kidus Markos, 6 = Mahdere Sbat Lideta, 7 = Mskaye Hzunan Medhaniyalem, 8 = Debre Ybab Yared, 9 = Menbere Hiwet Medhaniyalem, 10 = Debre Bisrat Kidus Gebreal, 11 = Bole Debre Selam Medhaniyalem, 12 = Hiwet Gebre Menfes Kidus, 13 = DebreMenkrat T/Haymanot, 14 = Debre Mitmaq Philipos, 15 = Beza Bzuhan Kidane Mihret, 16 = Debre Genet Kidus Mikael, 17 = Debre Genet Kidus Gebreal Kaliti.



Determination of forest area

The forest patches within each church boundary were measured for their areas and summed up for the total church forest areas. The delineation of forest patches area enhances accurate measurement and accounting of the forest carbon stock and woody species diversity. All forest patches were delineated using GPS track with the accuracy of about 3 m.

Data collection

A full inventory of all woody species with a diameter at breast height (DBH) of 5 cm and above was carried out in each church forest for carbon estimation and tree size determination. The woody plants DBH was measured by calliper/ diameter tape, but whenever there was more than one stem below 1.3 m height, separate measurements were carried out for each of the stems. Height was measured using Haga hypsometer. All the woody species having a height of 20 cm and above were counted in each church forest for the diversity assessment.

Vegetation identification

Plant identification was done in the field, and for those difficult ones to identify in the field, fresh specimens were

Fig. 2 Climate diagram of Addis Ababa
Data source: National Metrology Agency, 2016.

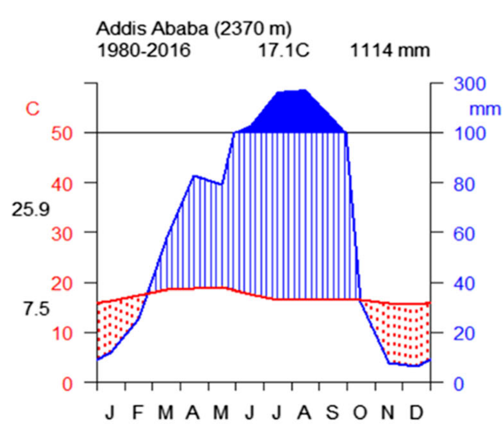


Table 1 List of seventeen selected churches, church age at the time of sampling, and the respective forest biomass and carbon stocks, abundance, tree species diversity indices and proportion of exotic species in each church

No.	Name of Church	Year of establishment	Age class	Age of Church (year)	Forest area (ha)	AGB t ha^{-1}	AGC t ha^{-1}	BGB t ha^{-1}	BGC t ha^{-1}	TCD t ha^{-1}	Native carbon t ha-1	Abundance	Shannon	Evenness	Simpsons	Richness	Exotic (%)	BA (m^2)
1	Dagmawi Debre Libanos Debre Amen Teklehaymanot	1897	Strata 1	119	0.49	349	164	69.7	32.8	197	133.5	248	2.29	0.72	0.84	24	46	17.7
2	Debre Gelila Amanueal	1913		103	0.51	351	165	70.1	33	198	50.1	426	2.12	0.64	0.75	28	**57**	21.1
3	Debre Negodgwad Kidus Yehuwans	1922		94	0.26	379	178	75.9	35.7	214	169.6	177	2.58	0.81	0.89	24	42	10.9
4	Genete Eyesus	1923		93	0.56	346	163	69.2	32.5	195	173.3	143	1.91	0.64	0.71	20	45	21.4
5	Menbere Liaul Kidus Markos	1924		92	0.13	396	186	79.1	37.2	223	200.5	148	2.21	0.74	0.83	20	**55**	7.4
6	Mahdere Sbat Lideta	1925		91	0.48	490	230	98	46	276	177.5	350	2.68	0.83	0.9	25	48	25.9
7	Mskaye Hzunan Medhaniyalem	1948	Strata 2	68	0.29	399	188	79.8	37.5	225	162.5	260	2.49	0.72	0.86	31	48	13.7
8	Debre Ybab Yared	1956		60	0.22	176	82.7	35.2	16.5	99.2	14.9	257	2.79	0.8	0.92	33	**52**	5.1
9	Menbere Hiwet Medhaniyalem	1963		53	0.88	365	172	73.1	34.3	206	20.1	887	1.18	0.38	0.47	23	48	28.3
10	Debre Bisrat Kidus Gebreal	1965		51	1.04	85.8	40.3	17.2	8.1	48.4	14.2	560	2.34	0.71	0.86	27	41	13.1
11	Bole Debre Selam Medhaniyalem	1980	Strata 3	36	1.27	24.6	11.5	4.9	2.3	13.9	7.5	743	3.21	0.81	0.94	54	**52**	20.9
12	Mierafe Kidus Felege Hiwet Gebre Menfes Kidus	1982		34	0.74	215	101	43.1	20.3	122	40.3	794	2.56	0.73	0.88	34	38	7.3
13	DebreMenkrat T/Haymanot	1986		30	2.42	150	70.6	30	14.1	84.7	8.5	1274	1.19	0.45	0.58	14	**71**	27
14	Debre Mitmaq Philipos	1987		29	0.17	314	148	62.8	29.5	177	100.8	268	1.97	0.68	0.82	18	39	3.5
15	BezaBzuhanKidaneMihret	1992	Strata 4	24	0.75	24.6	11.6	4.9	2.3	13.9	4.6	339	2.36	0.72	0.83	26	**54**	12.7
16	Debre Genet Kidus Mikael	1993		23	0.17	566	266	113	53.2	319	139.5	326	2.4	0.72	0.8	28	46	10.3
17	Debre Genet Kidus Gebreal Kaliti	1994		22	0.21	76.2	35.8	15.2	7.2	43	6.9	86	2.39	0.8	0.84	20	**60**	2.2
	Sum (all)				*10.59*	*4707.2*	*2213.5*	*941.2*	*442.5*	*2655.1*	*1424.1*	*7486*	*38.67*	*11.9*	*13.72*	*449*	*842*	*248.5*
	Mean (all)			*60*	*0.62*	*277*	*130*	*55.4*	*26.0*	*156*	*83.8*	*440.4*	*2.27*	*0.70*	*0.81*	*26*	*50*	*14.6*
	Standard deviation (all)			*33*	*0.57*	*163*	*77*	*32.7*	*15.4*	*92*	*75.1*	*339.1*	*0.51*	*0.12*	*0.12*	*9*	*8*	*8.4*

AGB = above ground biomass, AGC = above ground carbon, BA = Basal area, BGB = below ground biomass, BGC = below ground carbon, TCD = total carbon density collected, properly pressed, transported, further dried and deposited at the National Herbarium of the Addis Ababa University for subsequent identification.

Estimation of carbon stock

Equations developed via dimensional analysis were used for above-ground biomass estimation without destructive sampling following Jenkins et al. (2003). These equations are different depending on the type of species, geographical locations, forest stand types, climate and others. The church forests were largely uneven-aged and composed of both remnant/planted native trees and several exotic tree species. Hence, a generic allometric equation by Chave et al. (2014) was employed to estimate the above-ground biomass. The allometric equation considers DBH, height and density of trees. Thus, the above-ground biomass (AGB) was computed as:

$$AGB = 0.0673x\ \left(PxD^2xH\right)^{0.976} \tag{1}$$

Where:
AGB = above ground biomass in Kg.
P = density in g cm ^{3} (wood density of each tree species was obtained from global wood density database (Chave et al. 2009; Zanne et al. 2009).
D = diameter at breast height in cm.
H = height in m.

The below-ground biomass was calculated as constituting 20% of the above-ground tree biomass, following Merganič and Šmelko (2004). Then, a generic conversion factor of 0.47 was used to compute the carbon stocks from the biomass estimates as stipulated in Change (2006). Both the biomass and carbon stock were expressed in metric tons (t) and metric tons per hectare (t ha-1).

Analysis of woody species diversity, density and dominance

Different indicators could be computed for woody species richness, abundance, evenness and patterns of changes (Merganič and Šmelko 2004; Newton 2007), and the simultaneous use of different diversity indices is recommended for greater insight and better information (Magurran 2004; Morris et al. 2014). Thus, Shannon and Wiener (H′), Shannon evenness (J') and Simpson (1-D) were computed for each church forest as given in Magurran (2004). Also calculated were density (the abundance value of each species on per ha basis), relative density, dominance (basal area) and relative dominance values.

Statistical analysis

Analysis of variance (One-way ANOVA) was carried out to detect if there were significant differences among the four church age class strata on selected parameters, namely, forest area, carbon stock, density, basal area and the proportion of exotic trees in each church forest. Also, we carried out correlation analysis after viewing the linearity of relationships among all the variables in scatter plots and undertaking the Shapiro-Wilk normality test. Because some of the variables violated the assumptions for normal distribution, we opted to do Spearman's correlation tests. Both statistical tests were carried out in SPSS 20.

Result

Woody biomass and carbon stock (living above and below) of church forests

The results showed that the church forests had on average 0.6 ± 0.57 ha of size. They contained an estimated 332.3 ± 196.3 t ha-1 of woody biomass on average with above-ground biomass of 276.9 t ha-1 and below-ground biomass of 55.4 t ha-1. Therefore, there was 156 ± 92 t ha^{-1} of woody biomass carbon stock in the forests on average. From among the churches, the highest carbon stock was recorded in Debre Genet Kidus Mikael church (319 t ha^{-1}) (Table 1). Table 1 also shows that all the Strata I church forests had above average carbon stock.

The first three species with the highest total carbon stock in the church forests were *Juniperus procera*, *Eucalyptus globulus* and *Eucalyptus camaldulensis* (Table 2).

ANOVA revealed significant differences ($p < 0.05$) among the four Strata for carbon stock of native trees (Fig. 3), but there was not any significant difference for total carbon stock. The least-square differences (LSD) test revealed that the mean native trees' carbon stock in Strata I was significantly higher than the remaining three strata.

Species abundance, composition, diversity and tree size of church forests

The abundance value was the highest at Debre Menkrat T/Haymanot and the least at Debre Genet Kidus Gebreal Kaliti with a mean value of about 440 ± (339) across the churches (Table 1). The density of the woody species in each church forest didn't differ significantly among the four strata.

A total of 90 woody species belonging to 35 families were identified: 50 of the species were indigenous while the remaining 40 were exotic (Appendix Table 4). *Eucalyptus globulus, Juniperus procera, Eucalyptus camaldulensis, Cupressus lusitanica* and *Olea europaea subsp. cuspidata* were the five most abundant species in the 18 church forests. These same five tree species were the dominant ones in terms of the combined relative density and basal area but with a slightly different order: *Juniperus procera, Eucalyptus globulus, Eucalyptus camaldulensis, Olea europaea subsp. cuspidata* and *Cupressus lusitanica* (Table 2).

The highest numbers of woody species richness were recorded at Bole Medhaniyalem while the lowest was recorded in DebreMenkrat T/Haymanot church forests. The proportion of the exotic species (richness) ranged from 38% at Mierafe Kidus Felege Hiwet Gebre Menfes Kidus church forest to 71% at DebreMenkrat T/Haymanot church forest, and generally, about 47% of the church forests had a higher proportion of exotic species than the indigenous species (Table 1). The mean Shannon-Wiener diversity index, Simpsons index, and evenness values were 2.27 ± 0.51, 0.81 ± 0.12 and 0.7 ± 0.12, respectively (Table 1). ANOVA didn't reveal significant differences among the four Strata for density and proportion of exotic species. The mean basal area of the churches was 14.6 ± 8.4 m^2 ranging from 2.2 m^2 at Debre Genet Kidus Gebreal Kaliti to 28.3 m^2 at Menbere Hiwet Medhaniyalem (Table 1).

Relationship between the different church and tree parameters

The results from the correlation analysis indicated that the carbon stock of native trees had a significant positive relationship with the church age. However, there was no significant relationship between church age and total carbon stock, basal area and the proportion of exotic trees (Table 3). The forest size had a significant positive correlation with the basal area and significant negative correlations with the total carbon density and the native trees' carbon density. The size of the forest had no significant correlation with density, the diversity indices, the carbon stock and the proportion of exotic trees. The total

Table 2 List of the top 15 carbon stock, tree size and their abundance, density, basal area in seventeen church forests, in decreasing order of total carbon stock

No	Scientific Name	Abundance	Mean DBH	Mean Height	AGB t ha-^{1}	AGC t ha-^{1}	BGB t ha-^{1}	BGC t ha-^{1}	TCD t ha-^{1}	Density	RD	BA	RBA	Sum of RD & RBA
1	*Juniperus procera*	1066	20.1	14.6	1301.7	611.8	2245.3	260.3	122.4	449.1	734.2	95.4	32.5	32.9
2	*Eucalyptus globulus*	1096	17.9	19.4	612.4	287.8	1056.2	122.5	57.6	211.3	345.4	98	26.7	30
3	*Eucalyptus camaldulensis*	756	18	18.1	572.1	268.9	986.8	114.4	53.8	197.4	322.7	67.6	19.1	21.1
4	*Olea europaea subsp. cuspidata*	716	18.9	10.3	504.3	237	869.9	100.9	47.4	174	284.4	64	18.3	20.1
5	*Cupressus lusitanica*	752	13.8	11	272.5	128.1	470	54.5	25.6	94	153.7	67.3	10.6	16.1
6	*Casuarina cunninghamiana*	201	23.1	17.1	244.2	114.8	421.2	48.8	23	84.2	137.7	18	7.9	7.2
7	*Prunus africana*	130	19.2	12.9	174.7	82.1	301.4	34.9	16.4	60.3	98.5	11.6	3.5	3.8
8	*Grevillea robusta*	465	14.4	11.8	143.5	67.5	247.6	28.7	13.5	49.5	81	41.6	7	10.2
9	*Ficus sur*	92	27.3	13.5	130.5	61.3	225.1	26.1	12.3	45	73.6	8.2	5.1	4.2
10	*Casuarina equisetifolia*	77	22.9	17.1	120.8	56.8	208.3	24.2	11.4	41.7	68.1	6.9	3.1	2.8
11	*Cordia africana*	388	15.2	8.4	97.7	45.9	168.5	19.5	9.2	33.7	55.1	34.7	6.7	9
12	*Acacia melanoxylon*	160	15.3	12	81.2	38.2	140.1	16.2	7.6	28	45.8	14.3	2.6	3.6
13	*Millettia ferruginea*	60	22.6	14.9	65.2	30.7	112.5	13	6.1	22.5	36.8	5.4	2.3	2.1
14	*Acacia abyssinica*	62	27.1	11.4	48.4	22.7	83.4	9.7	4.5	16.7	27.3	5.5	3.4	2.8
15	*Ekebergia capensis*	25	16	6.4	34.2	16.1	59	6.8	3.2	11.8	19.3	2.2	0.4	0.6
	Other 58 species	1440	905.1	558.4	304.1	142.6	524.2	60.9	28.6	105.2	171.4	129.2	24.9	33.4
	Total	7486	1196.9	757.3	4707.5	2212.3	8119.5	941.4	442.6	1624.4	2655	669.9	174.1	200

AGB = above ground biomass, AGC = above ground carbon, BGB = below ground biomass, BGC = blow ground carbon, RD = relative density, BA = basal area, RBA = relative basal area, DBH = diameter at breast height

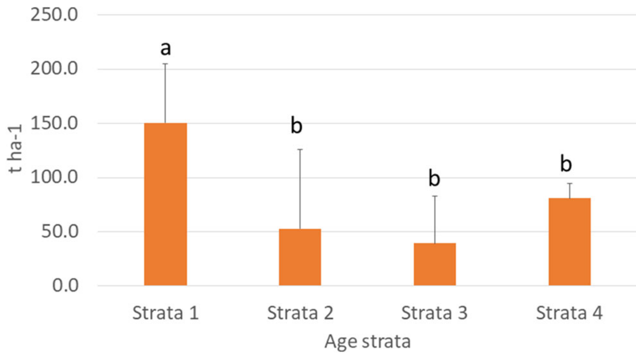


Fig. 3 Mean carbon stock due to native trees in different Church age strata in Addis Ababa. Bars with different letters differenced significantly ($p < 0.05$)

carbon density had a significant, positive relationship with density. Nonetheless, it didn't have a significant relationship with any of the diversity indices. Density had a significant positive relationship with exotic trees' total carbon density (Table 3).

Discussion

Carbon stock, density and diversity of woody species in church forests

The mean above-ground biomass in this study, 277 t ha^{-1}is a little above the global above-ground biomass estimates for tropical dry forests that range between 30 and 273 t ha^{-}1 (Murphy and Lugo 1986). In general, differences are expected because of the variations in age of the trees, management of the forests, the allometric model used (Lasco et al. 2000), regional variability in soil, topography, the existing species height and DBH range of trees.

The estimated mean woody biomass carbon stock (156 t ha^{-1}) was identical to the estimate for seven other church forests in Addis Ababa (Tura et al. 2013). The carbon stock was higher than the estimated mean amount for ten church forests (112.9 t ha-1) (Abiyu 2013) in Addis Ababa. Similarly, the current finding was higher than the mean carbon stock of eight parks (143.3 t ha-1) in Addis Ababa (Habtamu 2013). When compared with the findings of Woldegerima et al. (2017) at Mount Entoto forest of Addis Ababa that had differently stocked forest types, the carbon stock was higher than the open (132 t ha^{-1}) and medium (142 t ha^{-1}) forest types but much lower than the dense (293 t ha^{-1}) forest type. Therefore the variations observed in carbon stocks of the different forest types relate apparently to density and size and trees available in each. The highest total carbon stock for *Juniperus procera*, *Eucalyptus globulus* and *Eucalyptus camaldulensis* was mainly due to their high abundance in the forests.

The significantly higher carbon stock of native trees in Strata I (oldest churches) may indicate that the oldest churches were established in places where there were already remnant forests. It also indicates that the Church, in turn, preserved the forests to date notwithstanding natural tree deaths. Most of the younger churches were perhaps established in denuded areas and a few 'luckier' ones in the middle of remnant forests. Differences in plantation experiences and successes of native trees in the church compounds could also explain the observed patterns partially.

The biomass carbon stock was found distributed over 90 different woody species in the 17 church forests. The species composition in some of the churches was exotic dominated contrary to the expectations that church forests harbour more indigenous tree species because of the prevalence of old-aged natural forest patches in their compounds (Wassie et al. 2005). The high number of the exotic tree species in church forests than the expected could be due to the high availability of planting material, high plantation success, better market and better regeneration for the exotics than the native species.

The woody species density didn't differ significantly among the four strata perhaps because of random variation in stocking despite differences in establishment eras of the church forests. The Shannon diversity index is reported to fall between 1.5 and 3.5 in most ecological studies, and the mean Shannon diversity index (H`), 2.27, is a medium level of diversity. On the other hand, the Simpson (0.81) and evenness (0.71) values show the existence of acceptably high diversity levels within the church forests. The diversity values were contributed by both indigenous and exotic tree species that represented about 55% and 45% of the total woody species identified in the study areas, respectively. The heterogeneity indices recorded from each church were comparable to that of other church forests, which has Shannon diversity and Shannon evenness ranging from 2.0 to 3.1 and 0.63 to 0.82, respectively (Wassie 2002), and the present findings fall under this range. Comparison of the results with findings from other studies in Afromontane forests in the central Ethiopia shows that diversity indices were lower than figures reported for Woynwuha forest (i.e. Shannon diversity and evenness of 3.24 and 0.76, respectively) (Mekonen et al. 2015), and it was slightly higher than the Shannon diversity index (2.77) of Chilimo Afromontane forest (Gole 1998).

The total woody species richness recorded in the 17 church forests (90 species) was comparable with the findings of Tilahun et al. (2015) who reported 92 different plant species of which the majority were woody plants in six monasteries. A much higher number of species were reported by Wassie et al. (2010) in which 168 native and exotic tree species were recorded in 28 different churches signifying even the higher importance of church forests in forest genetic resources conservation. From the identified 50 native tree species, the abundance of the characteristic Afromontane undifferentiated forest species *Juniperus procera* and *Olea europaea subsp. cuspidata* may depict that the church forests still inhabit substantial remnant forest patches in their premises.

Differences in policy and institutions in the different age categories could have contributions to the observed patterns as the church age classes relate to the different eras and socioeconomic contexts therein. For example, Strata one churches mainly related to the Pre-Hailesellasie era and had the least number of species. This is the time when modern tree planting was started using introduced tree species, and it was the time when Emperor Menelik II sought solutions for alleviating the shortage of firewood and construction wood in the capital Addis Ababa (Eshetu 2014) but with an apparent focus in *Eucalyptus* species (Pankhurst 1961; Pohjonen and Pukkala 1990). Strata III, the Dergue era (1974 to 1991), had the highest number of species and it is the period that signifies the commencement of community plantations, large-scale plantations and peri-urban fuelwood plantations. Strata II Churches, which relate to the Emperor Hailesellasie era (1930–1974) and Strata IV Churches, which relate to the EPRDF regime (from 1991 to date), had species richness that falls between the two extremes. The Emperor Hailesellasie era was mainly characterized by exploitation of forest resources and agricultural modernization whereas the EPRDF is characterized by agricultural intensification, multi-actor forest governance and an overemphasis on the environmental role of forests (Ayana et al. 2013).

Relationship between carbon stock and tree size and church age and forest size

The significant positive association between carbon stock of native trees with the church age could be mainly related to the preservation of the native trees for a long time. The lack of significant relationship between church age and total carbon stock, basal area and the proportion of exotic trees, in general, could reflect the dynamism and the continuous shaping of the church forest compositions despite church establishment years.

Table 3 Spearman's correlation among age of church, forest area, basal areas, carbon stocks, density and proportion of exotic tree species in Addis Ababa church forests ($N = 17$)

Items	Church age	Forest area	TCD	Density	Shannon	Evenness	Simpson	Richness	Exotic (%)	BA	Exotic TCD
Forest area	−0.027	1									
TCD	0.441	−0.510*	1								
Density	−0.118	−0.455	0.483*	1							
Shannon	−0.051	−0.163	−0.025	0.164	1						
Evenness	0.027	−0.353	0.030	0.048	0.882**	1					
Simpson	0.095	−0.086	−0.143	0.065	0.921**	0.864**	1				
Richness	0.030	0.162	−0.042	0.304	0.715**	0.377	0.607**	1			
Exotic (%)	−0.098	0.067	−0.204	−0.298	−0.105	0.012	−0.189	−0.149	1		
BA	0.397	0.665**	0.172	−0.341	−0.341	−0.406	−0.331	−0.087	0.182	1	
Exotic TCD	0.027	−0.180	0.526*	0.620**	−0.113	−0.237	−0.243	0.082	−0.092	0.125	1
Native TCD	0.615**	−0.520*	0.858**	0.299	−0.022	0.128	−0.021	−0.160	−0.344	0.098	0.179

* Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level

The significant positive relationship between forest size and the basal area may show that the trees in big church compounds could grow bigger and older. However, there were significant negative correlations between the forest size and the total carbon density and native trees' carbon density. The reason for such differences could be due to the variations in height and wood density. The lack of significant relationship between forest size and density, the diversity indices, the carbon stock and the proportion of exotic trees, in a nutshell, indicates that ages of the woody species and the forest stoking in terms of number and type of species composition differed among the church forests randomly.

The significant positive relationship between total carbon stock and density shows that often high-density forest stands tend to have high carbon stock. Similarly, Behera et al. (2017) noted a strong positive correlation of the above-ground biomass with tree density in the Indian tropical forest. However, the condition of being even-aged monoculture and being uneven-aged and mixed-species would influence discussions on the effect of stand density on carbon stock (He et al. 2013). Also, the significant positive relationship between density and the exotic trees' carbon density but not with the native trees' carbon stock indicates that the exotic trees were more densely populated as compared to the native trees. The absence of a significant relationship between total carbon stock and any of the diversity indices in the church forests fits mathematical expectations since diversity is only about numbers and types whereas carbon stock is also about tree sizes. However, this is not a generalization as some scholars have also reported significant relationships between carbon stock and diversity owing to complex ecological processes (Cavanaugh et al. 2014; Poorter et al. 2015; Sullivan et al. 2017).

Conclusion

The study has reported on the carbon stock and woody species diversity patterns in four different church age strata in 17 church forests, which belonged to the Ethiopian Orthodox Churches that established during different political regimes, in Addis Ababa. It has also determined that the amount of carbon stock contained in each church forest was 156 ± 92 t ha-1 on average. Further, it has identified a total of 90 woody species belonging to 35 families. The diversity of the woody species was composed of 50 native and 40 exotic species. A significantly higher amount of carbon was recorded for native trees in Strata I, implying that the oldest churches had a better chance of being established in areas with remnant forests. Diversity patterns were random and didn't commensurate with the age of the church establishment as there could be dynamism in stocking and management of the church forests over the years. Forest areas also had significant influences on basal area, native trees carbon stock and proportion of exotic trees. Thus, the Churches provide sound forest protection allowing trees to grow big and old and manage a significant proportion of the trees for purposes other than wood production. Therefore, the essential role the church forests are playing to maintain woody species diversity and the associated biodiversity and their role in sequestering carbon dioxide need to be appreciated, and policy and institutional supports should be given to maximize these highly positive effects. The study clearly shows that the contribution of such small-sized forests (0.62 ha) for carbon sequestration, climate change mitigation and biodiversity conservation should be well recognized, and results are indicative of the potential roles of such small-sized forests in Ethiopia and elsewhere. Therefore, the practice of maintaining and developing such small-sized forests in church compounds and elsewhere in towns and cities should be scaled up as the integral components in urban green spaces through long-term development and management.

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Author contributions GY: Participated in conceptualization and setting objectives of the study, carried out the species identification, delineation of forest areas and data collection and data analysis and drafted the original draft and participated in correcting the manuscript after comments by the anonymous reviewers and the Editor.

AD: Conceptualized the study, carried out part of the data analysis, supervised the study, improved the original draft and handled the corrections of the manuscript after comments by the anonymous reviewers and the Editor and enriched the paper.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

Appendix

Table 4 List of tree species, origin, tree size, carbon stock, and their abundance, density, basal area in seventeen church forests, in decreasing order of total carbon stock

No.	Scientific Name	Family	Origin	Abundance	Mean DBH	Mean Height	AGB t ha^{-1}	AGC t ha-1	AGC CO2 t ha^{-1}	BGB t ha^{-1}	BGC t ha^{-1}	BGC CO2 t ha^{-1}	TCD t ha^{-1}	Density	BA (m^2)	Sum of RD & RBA
1	*Juniperus procera*	Cupressaceae	Native	1066	20.1	14.6	1301.7	611.8	2245.3	260.3	122.4	449.1	734.2	95.4	32.5	32.9
2	*Eucalyptus globulus*	Myrtaceae	Exotic	1096	17.9	19.4	612.4	287.8	1056.2	122.5	57.6	211.3	345.4	98	26.7	30
3	*Eucalyptus camaldulensis*	Myrtaceae	Exotic	756	18	18.1	572.1	268.9	986.8	114.4	53.8	197.4	322.7	67.6	19.1	21.1
4	*Olea europaea subsp. cuspidata*	Oleaceae	Native	716	18.9	10.3	504.3	237	869.9	100.9	47.4	174	284.4	64	18.3	20.1
5	*Cupressus lusitanica*	Cupressaceae	Exotic	752	13.8	11	272.5	128.1	470	54.5	25.6	94	153.7	67.3	10.6	16.1
6	*Casuarina cunninghamiana*	Casuarinaceae	Exotic	201	23.1	17.1	244.2	114.8	421.2	48.8	23	84.2	137.7	18	7.9	7.2
7	*Prunus africana*	Rosaceae	Native	130	19.2	12.9	174.7	82.1	301.4	34.9	16.4	60.3	98.5	11.6	3.5	3.8
8	*Grevillea robusta*	Proteaceae	Exotic	465	14.4	11.8	143.5	67.5	247.6	28.7	13.5	49.5	81	41.6	7	10.2
9	*Ficus sur*	Moraceae	Native	92	27.3	13.5	130.5	61.3	225.1	26.1	12.3	45	73.6	8.2	5.1	4.2
10	*Casuarina equisetifolia*	Casuarinaceae	Exotic	77	22.9	17.1	120.8	56.8	208.3	24.2	11.4	41.7	68.1	6.9	3.1	2.8
11	*Cordia africana*	Boraginaceae	Native	388	15.2	8.4	97.7	45.9	168.5	19.5	9.2	33.7	55.1	34.7	6.7	9
12	*Acacia melanoxylon*	Fabaceae	Exotic	160	15.3	12	81.2	38.2	140.1	16.2	7.6	28	45.8	14.3	2.6	3.6
13	*Millettia ferruginea*	Fabaceae	Native	60	22.6	14.9	65.2	30.7	112.5	13	6.1	22.5	36.8	5.4	2.3	2.1
14	*Acacia abyssinica*	Fabaceae	Native	62	27.1	11.4	48.4	22.7	83.4	9.7	4.5	16.7	27.3	5.5	3.4	2.8
15	*Ekebergia capensis*	Meliaceae	Native	25	16	6.4	34.2	16.1	59	6.8	3.2	11.8	19.3	2.2	0.4	0.6
16	*Afrocarpus falcatus*	Podocarpaceae	Native	77	12.2	7.8	24.7	11.6	42.6	4.9	2.3	8.5	13.9	6.9	0.8	1.5
17	*Schinus molle*	Anacardiaceae	Exotic	81	19.4	9.8	21.7	10.2	37.4	4.3	2	7.5	12.2	7.2	2.2	2.4
18	*Phoenix reclinata*	Arecaceae	Native	97	30.8	4.8	21	9.9	36.3	4.2	2	7.3	11.9	8.7	5.4	4.4
19	*Dracaena steudneri*	Asparagaceae	Native	58	19.4	8.7	17.9	8.4	30.9	3.6	1.7	6.2	10.1	5.2	1.5	1.6
20	*Olinia rochetiana*	Oliniaceae	Native	38	17.9	12.1	17.1	8.1	29.6	3.4	1.6	5.9	9.7	3.4	0.9	1
21	*Strychnos spinosa*	Loganiaceae	Native	43	14.9	8.7	16.1	7.6	27.7	3.2	1.5	5.6	9.1	3.8	0.8	1
22	*Acacia mearnsii*	Fabaceae	Exotic	21	15.9	13.3	15.8	7.4	27.3	3.2	1.5	5.5	8.9	1.9	0.4	0.5
23	*Morus mesozygia*	Moraceae	Native	19	16.5	9.7	15.6	7.3	26.9	3.1	1.5	5.4	8.8	1.7	0.4	0.5
24	*Eucalyptus saligna*	Myrtaceae	Exotic	2	57.6	33	15.3	7.2	26.4	3.1	1.4	5.3	8.6	0.2	0.5	0.3
25	*Acacia decurrens*	Fabaceae	Exotic	38	18.7	11.2	13.9	6.5	23.9	2.8	1.3	4.8	7.8	3.4	0.8	1
26	*Acacia lahai*	Fabaceae	Native	14	21	11	9.6	4.5	16.6	1.9	0.9	3.3	5.4	1.3	0.4	0.4
27	*Borassus aethiopum*	Arecaceae	Native	24	24.1	6.9	9.5	4.4	16.3	1.9	0.9	3.3	5.3	2.1	0.6	0.7
28	*Vernonia amygdalina*	Asteraceae	Native	169	12	7.8	9.4	4.4	16.1	1.9	0.9	3.2	5.3	15.1	1.7	3.2
29	*Jacaranda mimosifolia*	Bignoniaceae	Exotic	91	12.9	9.8	9.3	4.4	16.1	1.9	0.9	3.2	5.3	8.1	1.1	1.9
30	*Acacia saligna*	Fabaceae	Exotic	17	21.6	9	9.3	4.4	16	1.9	0.9	3.2	5.2	1.5	0.6	0.6
31	*Persea americana*	Lauraceae	Exotic	42	14.7	8	7.1	3.3	12.3	1.4	0.7	2.5	4	3.8	0.6	0.9

Table 4 (continued)

No.	Scientific Name	Family	Origin	Abundance	Mean DBH	Mean Height	AGB t ha^{-1}	AGC t ha-1	AGC CO2 t ha^{-1}	BGB t ha^{-1}	BGC t ha^{-1}	BGC CO2 t ha^{-1}	TCD t ha^{-1}	Density	BA (m^2)	Sum of RD & RBA
32	*Spathodea nilotica*	Bignoniaceae	Exotic	57	14.8	10.5	6.6	3.1	11.5	1.3	0.6	2.3	3.7	5.1	0.9	1.3
33	*Hagenia abyssinica*	Rosaceae	Native	17	14.8	7.3	5.3	2.5	9.1	1.1	0.5	1.8	3	1.5	0.2	0.4
34	*Corymbia citriodora*	Myrtaceae	Exotic	2	25.4	20.3	5	2.4	8.7	1	0.5	1.7	2.8	0.2	0.1	0.1
35	*Erythrina brucei*	Fabaceae	Native	10	27.7	17	4.7	2.2	8.2	1	0.4	1.6	2.7	0.9	0.6	0.5
36	*Casimiroa edulis*	Rutaceae	Exotic	36	12.3	9.3	4.6	2.1	7.9	0.9	0.4	1.6	2.6	3.2	0.4	0.7
37	*Ficus carica*	Moraceae	Exotic	3	34.5	18.8	4	1.9	7	0.8	0.4	1.4	2.3	0.3	0.2	0.1
38	*Azadirachta indicia*	Meliaceae	Exotic	10	15	8.7	3.8	1.8	6.5	0.8	0.4	1.3	2.1	0.9	0.1	0.2
39	*Combretum molle*	Combretaceae	Native	4	22.7	8.8	3.7	1.8	6.5	0.8	0.4	1.3	2.1	0.4	0.2	0.1
40	*Callistemon citrinus*	Myrtaceae	Exotic	28	11.6	5.7	3.6	1.7	6.3	0.7	0.3	1.3	2.1	2.5	0.2	0.5
41	*Bersama abyssinica*	Melianthaceae	Native	9	17.4	7	3.5	1.6	6	0.7	0.3	1.2	2	0.8	0.2	0.2
42	*Eucalyptus grandis*	Myrtaceae	Exotic	5	18.3	22.2	3.2	1.5	5.5	0.6	0.3	1.1	1.8	0.4	0.1	0.1
43	*Faidherbia albida*	Fabaceae	Native	10	15.4	9.7	3.2	1.5	5.5	0.6	0.3	1.1	1.8	0.9	0.2	0.2
44	*Acacia senegal*	Fabaceae	Native	11	13.4	8.6	2.4	1.1	4.1	0.5	0.2	0.8	1.4	1	0.1	0.2
45	*Shirakiopsis elliptica*	Euphorbiaceae	Exotic	4	21.3	16.5	2.2	1	3.8	0.4	0.2	0.8	1.2	0.4	0.1	0.1
46	*Euphorbia abyssinica*	Euphorbiaceae	Native	3	28.1	17.5	1.4	0.7	2.5	0.3	0.1	0.5	0.8	0.3	0.1	0.1
47	*Melia azedarach*	Meliaceae	Exotic	40	13.5	5.9	1.4	0.6	2.3	0.3	0.1	0.5	0.8	3.6	0.5	0.8
48	*Dombeya torrida*	Malvaceae	Native	5	20.4	11.3	1.2	0.6	2.1	0.2	0.1	0.4	0.7	0.4	0.2	0.2
49	*Citrus reticulata*	Rutaceae	Exotic	3	10.3	10.2	1.1	0.5	2	0.2	0.1	0.4	0.6	0.3	0	0.1
50	*Vepris nobilis*	Rutaceae	Native	18	13.5	7.8	0.9	0.4	1.6	0.2	0.1	0.3	0.5	1.6	0.1	0.3
51	*Erica arborea*	Ericaceae	Native	72	8.8	6.9	0.9	0.4	1.5	0.2	0.1	0.3	0.5	6.4	0.4	1.2
52	*Salix mucronata*	Salicaceae	Native	5	25.8	5.3	0.8	0.4	1.4	0.2	0.1	0.3	0.5	0.4	0.1	0.1
53	*Allophylus abyssinica*	Sapindaceae	Native	1	18.3	21	0.9	0.4	1.5	0.2	0.1	0.3	0.5	0.1	0.1	0.1
54	*Sesbania sesban*	Fabaceae	Exotic	26	8.9	6.7	0.8	0.4	1.3	0.2	0.1	0.3	0.4	2.3	0.2	0.4
55	*Ficus elastica*	Moraceae	Exotic	18	8.8	5.9	0.8	0.4	1.3	0.2	0.1	0.3	0.4	1.6	0.1	0.3
56	*Dovyalis abyssinica*	Salicaceae	Native	41	7.2	5.7	0.7	0.3	1.2	0.1	0.1	0.2	0.4	3.7	0.1	0.6
57	*Rhamnus prinoides*	Rhamnaceae	Native	10	8	6.3	0.6	0.3	1	0.1	0.1	0.2	0.3	0.9	0.1	0.2
58	*Pinus patula*	Pinaceae	Exotic	17	9.7	7.1	0.6	0.3	1.1	0.1	0.1	0.2	0.4	1.5	0.1	0.3
59	*Ficus vasta*	Moraceae	Native	14	10.2	5.8	0.5	0.2	0.8	0.1	0.1	0.2	0.3	1.3	0.1	0.2
60	*Croton macrostachyus*	Euphorbiaceae	Native	12	12.7	7.2	0.5	0.2	0.8	0.1	0	0.2	0.3	1.1	0.1	0.2
61	*Citrus sinensis*	Rutaceae	Exotic	7	7.8	6.8	0.5	0.2	0.8	0.1	0	0.2	0.3	0.6	0	0.1
62	*Ficus sycomorus*	Moraceae	Native	12	12.7	6.2	0.4	0.2	0.6	0.1	0	0.1	0.2	1.1	0.2	0.2
63	*Albizia gummifera*	Fabaceae	Native	2	8.6	14.5	0.3	0.1	0.5	0.1	0	0.1	0.2	0.2	0	0
64	*Araucaria jussieu*	Araucariaceae	Exotic	19	9.6	5.9	0.2	0.1	0.3	0	0	0.1	0.1	1.7	0.1	0.3
65	*Mangifera indica*	Anacardiaceae	Exotic	7	10.4	6.7	0.2	0.1	0.3	0	0	0.1	0.1	0.6	0	0.1

Table 4 (continued)

No.	Scientific Name	Family	Origin	Abundance	Mean DBH	Mean Height	AGB t ha^{-1}	AGC t ha-1	AGC CO2 t ha^{-1}	BGB t ha^{-1}	BGC t ha^{-1}	BGC CO2 t ha^{-1}	TCD t ha^{-1}	Density	BA (m^2)	Sum of RD & RBA
66	*Prunus persica*	Rosaceae	Exotic	6	8.6	6.2	0.1	0	0.1	0	0	0	0	0.5	0	0.1
67	*Buddleia polystachya*	Scrophulariaceae	Native	3	10.3	5	0.1	0	0.1	0	0	0	0	0.3	0	0.1
68	*Acacia seyal*	Fabaceae	Native	3	9	5.5	0.1	0	0.1	0	0	0	0	0.3	0	0.1
69	*Citrus aurantifolia*	Rutaceae	Exotic	4	5.2	8	0	0	0	0	0	0	0	0.4	0	0.1
70	*Psidium guajava*	Myrtaceae	Exotic	7	5.5	3.5	0	0	0	0	0	0	0	0.6	0	0.1
71	*Dichrostachys cinerea*	Fabaceae	Native	2	6.5	5	0	0	0	0	0	0	0	0.2	0	0
72	*Cupresuss pyramidalis*	Cupressaceae	Exotic	8	6.5	8	0	0	0	0	0	0	0	0.7	0	0.1
73	*Berchemia discolor*	Rhamnaceae	Exotic	1	6	4.5	0	0	0	0	0	0	0	0.1	0	0
74	*Trichilia dregeana*	Meliaceae	Native	3	0	0	0	0	0	0	0	0	0	0.3	0	0
75	*Rosa abyssinica*	Rosaceae	Native	9	0	0	0	0	0	0	0	0	0	0.8	0	0.1
76	*Pinus radiata*	Pinaceae	Exotic	1	0	0	0	0	0	0	0	0	0	0.1	0	0
77	*Morus alba*	Moraceae	Exotic	1	0	0	0	0	0	0	0	0	0	0.1	0	0
78	*Malus domestica*	Cupressaceae	Exotic	1	0	0	0	0	0	0	0	0	0	0.1	0	0
79	*Hibiscuc rosa-sinensis*	Malvaceae	Exotic	4	0	0	0	0	0	0	0	0	0	0.4	0	0.1
80	*Euphorbia tirucalli*	Euphorbiaceae	Native	1	0	0	0	0	0	0	0	0	0	0.1	0	0
81	*Eriobotrya japonica*	Rosaceae	Exotic	1	0	0	0	0	0	0	0	0	0	0.1	0	0
82	*Dodonaea viscosa*	Sapindaceae	Native	2	0	0	0	0	0	0	0	0	0	0.2	0	0
83	*Cytisus proliferus*	Fabaceae	Exotic	1	0	0	0	0	0	0	0	0	0	0.1	0	0
84	*Coffea arabica*	Rubiaceae	Native	4	0	0	0	0	0	0	0	0	0	0.4	0	0.1
85	*Celtis africana*	Celtidaceae	Native	1	0	0	0	0	0	0	0	0	0	0.1	0	0
86	*Carissa spinarum*	Apocynaceae	Native	4	0	0	0	0	0	0	0	0	0	0.4	0	0.1
87	*Calotropis procera*	Asclepiadaceae	Native	1	0	0	0	0	0	0	0	0	0	0.1	0	0
88	*Caesalpinia decapetala*	Fabaceae	Exotic	1	0	0	0	0	0	0	0	0	0	0.1	0	0
89	*Bridelia micrantha*	Euphorbiaceae	Native	1	0	0	0	0	0	0	0	0	0	0.1	0	0
90	*Acokanthera schimperi*	Apocynaceae	Native	1	0	0	0	0	0	0	0	0	0	0.1	0	0
	Sum			7486	1196.9	757.3	4707.5	2212.3	8119.5	941.4	442.6	1624.4	2655	669.9	174.1	200

AGB = above ground biomass, AGC = above ground carbon, BGB = below ground biomass, BGC = blow ground carbon, RD = relative density, BA = basal area, RBA = relative basal area, DBH = diameter at breast height

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