Relationship between carbon stocks and tree species diversity in a humid Guinean savannah landscape in Northern Sierra Leone

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Abstract

Global sustainable development goals include reducing greenhouse gas emissions from land use change and maintaining biodiversity. Many studies have examined carbon stocks and tree species diversity, but few have studied the humid Guinean savannah ecosystem. This study focuses on a humid savannah landscape in Northern Sierra Leone, aiming to assess carbon stocks and tree species diversity and compare their relationships in different vegetation types. We surveyed 160 sample plots (0.1 ha) in the field for tree species, aboveground carbon (AGC) and soil organic carbon (SOC). In total, 90 tree species were identified in the field. *Gmelina arborea*, an exotic tree species common in the foothills of the Kuru Hills Forest Reserve, and *Combretum* *glutinosum, Pterocarpus erinaceous* and *Terminaria glaucescens*, typical savannah trees, were the most common species. At landscape level, the mean AGC stock was 29.4 Mg C ha^{-1} (SD 21.3) and mean top-soil (0–20 cm) SOC stock was 42.2 Mg C ha^{-1} (SD 20.6). Mean tree species richness and Shannon index per plot were 7 (SD 4) and 1.6 (SD 0.6), respectively. Forests and woodlands had significantly higher mean AGC and tree species richness than bushland, wooded grassland or cropland ($p < 0.05$). In the forest and bushland, a small number of large diameter trees covered a large share of the total AGC stocks. Furthermore, a moderate linear correlation was found between AGC and tree species richness ($r = 0.475$, $p < 0.001$) and AGC and Shannon index ($r = 0.375$, $p < 0.05$). The correlation between AGC and SOC was weak ($r = 0.17$, $p < 0.05$). The results emphasize the role of forests and woodlands and large diameter trees in retaining AGC stocks and tree species diversity in the savannah ecosystem.

Keywords: tree species; aboveground carbon; soil organic carbon

1. Introduction

Savannahs are an important component of global vegetation as they cover more than 10% of the global land surface (Scholes and Walker 1993) and account for 30% of primary production of global terrestrial biomes (Grace et al. 2006). Global carbon stocks of forests are estimated to be 861 ± 66 Pg C, of which 44% is stored in soil, 42% in living biomass (aboveground and belowground) and the rest in deadwood and litter (Pan et al. 2011). Meanwhile, tropical savannah and grassland store 336 Pg C (Carvalhais et al. 2014), but soils contain at least as much carbon as stored in the biomass (Anderson 1991, Eswaran et al. 1993, Scholes and Hall 1996). This is because carbon in the aboveground pool tends to be more responsive to changes in disturbance regime (Higgins et al. 2007).

In addition to the carbon stocks, savannahs harbour a vast number of plant species and are important for global biodiversity (Abreu et al. 2017). These plant species support ecosystem functions (Abreu et al. 2017) and play a substantial role in the global carbon cycle (Majumdar et al. 2016). However, tree cover in the savannahs is affected by deforestation and degradation, leading to climate change and biodiversity loss (Strassburg et al. 2010, Thomas et al. 2004, Talbot 2010). Pellegrini et al. (2015) reported a large carbon-diversity trade-off between the maintenance of endemic savannah species and the promotion of carbon storage through woody plant cover. Finding such synergies between climate change mitigation and biodiversity conservation could be elementary for attaining goals 13 and 15 of the sustainable development goals. These include actions to combat climate change and land degradation and actions to halt biodiversity loss through sustainable forest management.

In Africa, savannahs cover even ca 50% of the terrestrial territory (Grace et al. 2006), which emphasize their role in the continental carbon cycle and biodiversity. However, despite their role to humans and potential for carbon storage, African savannahs remain rather poorly studied in comparison to other biomes (Jeltsch et al. 2017, Scholes and Archer 1997). African savannahs are distributed in Sahelian, Sudanese and Guinean zones (CILSS 2016). Part of the savannahs, such as the humid Guinean savannahs, have lost their original forest cover as a result of anthropogenic interference (CEPF 2000). The Guinean savannahs contain diverse forest habitats that provide refuges to numerous species, and the region is considered a global priority region for conservation because of the high endemism of flora and fauna (Bakarr et al. 2004). The humid Guinean savannah of Sierra Leone is an ecotone between the tropical rainforest and the Sudanese savannah characterized by high precipitation. The high annual precipitation in this biome enhances woody canopy closure, and disturbances (e.g. fire, grazing) are required for the coexistence of trees and grasses (Sankaran et al. 2005). Therefore, the biotic and abiotic drivers and processes play an important role in the current woody species distribution and composition as well as ecosystem functioning (Oliveras and Malhi 2016).

Information on carbon stocks by vegetation type is important for the implementation of Reducing emissions from deforestation and forest degradation (REDD+) but unfortunately, data on biomass and soil carbon stocks for Sierra Leone are poorly available. The database of UNEP-WCMC (2011) estimates the total terrestrial carbon stock of Sierra Leone to be 944 Mt, of which 519 Mt is allocated in the soil and 425 Mt in biomass. The distribution of the carbon stocks is uneven, with low carbon stocks in biomass but high soil carbon for more than 40% of the land (UNEP-WCMC 2011). Using remote-sensing methods, Bouvet et al. (2018) estimated AGC stock in Sierra

Leone’s savannah to be 276 Mt C, which lies between the estimates based on Saatchi et al. (2011) and Avitabile et al. (2016), 346 Mt C and 215 Mt C, respectively. Therefore, more information is required, particularly on carbon stocks and biodiversity in the Sierra Leone’s savannah region at the scale relevant for land management planning.

Many studies have examined the relationship between biodiversity (tree species diversity) and carbon stocks (biomass and soil), but the results are contradictory (Mensah et al. 2016a). Gamfeldt et al. (2015) and Dayamba et al. (2016) reported a positive relationship between the tree species diversity and multiple ecosystem services, such as biomass and soil carbon stocks, in different biomes. Filqisthi and Kaswanto (2017) and Zimudzi et al. (2016), on the other hand, reported no relationship between the tree species diversity and carbon stocks for pekarangan home gardens in West Java, Indonesia, and in Ngomakurira Mountain, Zimbabwe, respectively. Sharma et al. (2010) observed that forest types with higher tree species diversity had relatively low aboveground carbon (AGC) stocks in Garwal Himalaya, India. Furthermore, Kirby and Potvin (2007) and Saha et al. (2009) did not observe a clear relationship between soil organic carbon (SOC) stocks and tree species diversity in Eastern Panama and home gardens in Kerala, India, respectively. However, Chen (2006) reported a positive relationship for old growth forest in Changbai Mountain, China. While relationships between carbon stocks and biodiversity have been studied in various ecosystems and forest types, such results are not available for Sierra Leone’s savannah region.

The objective of this study was to assess carbon stocks and tree species diversity and their relationships in a Guinean forest-savannah landscape in Northern Sierra Leone. More specifically, AGC, SOC and tree species composition, richness and diversity were inventoried and examined per vegetation type and stem diameter class. Furthermore, the linear relationships between the different variables were studied by correlation analysis to examine if AGC and SOC are related to tree species diversity in the study area.

2. Materials and methods

2.1 Study area

The study area is 100 km^2 in Northern Sierra Leone (Fig. 1). The closest community to the site was Sanya village. A part of the study area (70 km^2) was in Kuru Hills Forest Reserve (Fig. 2a, Fig. 2b). The climate is monsoon-type humid tropical with a unimodal raining season, lasting for about six months from May to October (Gomez Paloma and Acs 2012). According to Hijmans et al. (2005), annual mean rainfall is 2244 mm and monthly mean temperature ranges between 23°C and 29°C. Topographically, the site is in the interior plateaus with low rolling hills. The elevations range from approximately 30 m a.sl. in the plateau to 700 m a.s.l. in Kuru Hills.

The main vegetation type in the landscape is tree savannahs of broad-leaved deciduous trees with a continuous ground cover of perennial bunch grasses and forbs (Fig. 2c). Some examples of common tree species are *Pterocarpus erinaceus* and *Parkia biglobosa,* and typical grasses include *Andropogon gabonensis* and *Andropogon tectorum*. The species composition varies per abiotic factors (moisture regime, soil type) and by the type and degree of disturbance (fire, anthropogenic, and grazing). During the rainy season, vegetation is green and covered with tall grasses that grow and reach maturity rapidly, thus becoming fibrous and tough. In the dry season, grasses tend to dry and disappear due to periodic bush-burning between

November and April (Fig. 2d, Fig. 2f). Forests are moist with deciduous or semi-evergreen species and found on the banks of rivers or streams and in the protected area in Kuru Hills (Fig. 2a). The main livelihood in the region is agriculture, primarily slash-and-burn cultivation for food but also market gardening and agroforestry (Fig. 2e). Livestock farming and timber harvesting are also common (Sierra Leone scoping report for the Building biocarbon and rural development in West Africa project, 2014, unpublished). Non-timber forest products (mainly honey, fruits, medicine and hunting) provide additional support for inhabitants of the region.

2.2 Sampling design

Data collection took place between April and May 2014 using the land degradation surveillance framework (LDSF) sampling design (Vågen et al. 2013). LDSF is intended to provide a biophysical baseline at landscape level and a monitoring and evaluation framework for assessing processes of land degradation and the effectiveness of landscape rehabilitation measures over time. The sampling is built around a hierarchical field survey and sampling protocol using sites that are 100 km^2 (10 km × 10 km) in size. The site comprised of sixteen 100 ha clusters (radius 564 m) that consisted of ten sample plots each, making a total of 160 plots. Because of the stratified random sampling strategy, clusters were located both in the plateau and in the Kuru hills forest reserve (Fig. 1). The sample plots were circular in shape with 0.1 ha main plot (radius 17.84 m) and four 0.01 ha sub-plots (radius 5.64 m) (Fig. 3).

The sample plots were stratified into vegetation types for analysis according to White (1983) classification (Table 1) used in the LDSF survey (Vågen et al. 2013). Thickets and shrubland were incorporated into bushland and grassland into wooded grassland because those plots were very few and had similar characteristics.

2.3 Inventory and tree diversity indices

Trees with a diameter at breast height (DBH) > 10 cm, including palms, were recorded in the main plot (0.1 ha) using calliper or diameter tape. Heights (H) of sample trees with the largest, median and smallest DBH were also measured using a hypsometer or a measurement pole. Crown diameter in two directions (the widest width and perpendicular direction) of the sampled trees were measured using a measuring tape. Trees with DBH of 4–10 cm were counted in the sub-plots (0.01 ha), and DBH, H and crown diameter were measured for median DBH trees. Botanical names of the trees were based on Savill and Fox (1967), but some species (6.8%) could not be identified. The two-parameter Curtis's function (Curtis 1967) and non-linear mixed-effects model with plot as random effects was used for H-DBH modelling (Valbuena et al. 2016). The model was used to predict H for all the trees with only DBH measured in the field. The modelling was carried out using 'nlme' package (Pinheiro et al. 2014) in R statistical software (R Core Team 2015).

The tree species diversity indices included species richness (S), defined as the total number of species present in the plot, and Shannon diversity index (H´):

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

where p_i is the relative abundance (share of the total number of stems) of each species (i = 1, 2, …, S) (Krebs 1999). Shannon diversity index was selected as it accounts for abundance and evenness of both species. Shannon index was set to zero when there were no trees present in the plots.

2.4 Aboveground biomass and carbon stock

Tree aboveground biomass (AGB) was computed using the most recent pan-tropical biomass models (Chave et al. 2014) because of the absence of local, species-specific allomeric equations. The model is based on DBH (cm), H (m) and wood-specific gravity (ρ, g/m^3):

$$AGB = 0.06773\ (\rho \times DBH^2 \times H)^{0.976}.$$

The values of ρ were sourced from online databases (Zanne et al. 2010, World Agroforestry Center 2015) to the closest taxonomic unit. As a result, 83.3% of stems had ρ available for species level, 93.2% for genus level and 93.4% for family level. For the unknown species, a site-specific mean value was used. AGB of palms was computed using the function of Frangi and Lugo (1985) based on height. Finally, AGB was converted to tree AGC stock (Mg ha^{-1}) using a carbon fraction of 0.47 (IPCC 2006, Paustian et al. 2006).

2.5 Soil carbon stock

Two types of soil samples were collected in the field: composite and cumulative mass samples They were collected using a soil auger with a sampling plate as auger guide, press firmly onto the soil. The auger was marked at 20, 50, 80 and 110cm. The composite samples were collected at sub-plot (0.01ha) level and used for the analysis of carbon content, while cumulative mass soil samples were collected to estimate bulk density, which is required to calculate SOC stocks (Aynekulu et al. 2011).

Top (0–20 cm) and sub (20–50 cm) soil samples were collected from the centre of each sub-plot. There were restrictions below 20 cm depth in most of the plots.

However, 0–20 cm depth was free of restriction in all the plots, and since most of the SOC is concentrated in the top 0–10 cm depth (Corbeels et al. 2016), we used only soil samples from 0–20 cm depth in this study. Therefore, samples with 0–20 cm depth were collected from sub-plots, mixed and a composite sample taken for laboratory analysis. SOC concentration (g kg^{-1}) was analysed using a thermal oxidation method (Liang et al. 2008, Skjemstad and Baldock 2008) in the soil laboratory of the World Agroforestry Centre in Nairobi, Kenya. To avoid the influence of inorganic carbon (carbonate), samples were treated with hydrochloric acid to remove the inorganic carbon (Harris et al. 2001). The gravimetric moisture content on a subsample was determined to calculate the actual oven-dried (105ºC) mass of the respective samples. SOC stock (Mg C ha^{-1}) was calculated as: SOC stock = $C/100 \times \rho \times D \times 10\,000$, where C is the soil organic concentration of fine soil fraction (< 2 mm diameter) determined in the laboratory (%), ρ is dry soil bulk density fine soil fraction (Mg m^{-3}), D is thickness of the sampled soil layer (m), and 10 000 is a factor for converting Mg C m^{-2} to Mg C ha^{-1}. SOC stock calculation was determined for the fine soil mass by excluding stones and coarse fragments. Bulk density was determined by dividing the soil mass with the volume of soil removed by the auger. The diameter of the auger was 7.6 cm, and the volume of the soil for the 20 cm soil thickness was 907 cm^3.

2.6 Statistical analysis

First, the plot-level values were used for computing descriptive statistics (mean, range and standard deviation) for the landscape. Next, AGC, SOC, species richness and Shannon index were analysed according to vegetation types. Kruskal-Wallis and pairwise Wilcoxon rank-sum tests were conducted to study if differences between the vegetation types were statistically significant. The non-parametric tests were used because the data set did not satisfy the assumptions of parametric tests. Bar plots were used to visualize how variables depended on grouping. Also, tree species composition between the vegetation types was compared, and stem density, AGC and species richness were studied according to the diameter class. Finally, the relationships between the carbon and tree species diversity variables were investigated using correlation analysis (Spearman's rank correlation coefficient). All the analyses were performed in R statistical software version 3.1.0 (R Core Team 2015).

3. Results

3.1 Carbon and tree species diversity at landscape level

AGC ranged from 0.2 to 113.1 Mg C ha^{-1} with a mean of 29.4 Mg C ha^{-1} (SD 21.3) (Table 2). SOC for depth 0–20 cm varied less than AGC but had higher mean value of 42.2 Mg C ha^{-1} (SD 20.6). Tree species richness varied between 1 and 17 with a mean of 7 species per plot (SD 4). Shannon index revealed a minimum and maximum of 0 and 2.4 with a mean of 1.6 (SD 0.6).

In total, 90 tree species were recorded, but scientific names could not be identified for 29 species (6.8% of the stems). The identified species belonged to 18 families and 53 genera. *Fabaceae* (*Leguminosae*) accounted for the largest number of species (19 species) followed by *Anacardiaceae* (5), *Annonaceae*, *Combretaceae*, *Malvaceae* and *Rubiaceae* (4). *Gmelina arborea,* an exotic tree species, showed the highest abundance (12.7%) in terms of stem count (Fig. 4). Indigenous species, *Combretum glutinosum* (12.5%)*, Pterocarpus erinaceous* (9.2%) and *Terminaria glaucescens* (6.4%), were also common in the landscape. The same species accounted for the highest amount of AGC stock. *P. erinaceous* contributed to the largest AGC share (16.8%) followed by *G. arborea* (14.7%), *C. glutinosum* (11.9%) and *T. glaucescens* (7.8%).

When analysing the data by DBH class (Table 3), it was evident that there were a large number of small stems (4–10 cm), which made only minor contributions to the total AGC. The number of stems decreased continuously towards the larger diameter classes. In terms of AGC, the most important DBH classes were between 10.1 and 50 cm, accounting for more than two-thirds of the total AGC stock (80.4%), with each class covering more than 10% of the total. Similarly, DBH range 4–50 cm accounted for the highest number of species, each covering more than 12% of the total number of species. Furthermore, the largest trees (DBH > 60 cm) covered a major fraction of the total AGC (11.7%), considering the small fraction of the total number of stems (0.4 %).

3.2 Carbon and tree species diversity in different vegetation types

In total, data were collected from 160 plots with different vegetation types: forest (29), bushland (11), cropland (25), wooded grassland (27) and woodland (68). The Kruskal-Wallis test revealed that all the variables differed significantly ($p < 0.001$) between the vegetation types. According to the Wilcoxon test (Fig. 5a), mean AGC of the forest (40.1 Mg C ha^{-1}, SD 24.6) and woodland (39.8 Mg C ha^{-1}, SD 12.1) were significantly higher than the mean AGC of the bushland (9.7 Mg C ha^{-1}, SD 5.1), wooded grassland (16.2 Mg C ha^{-1}, SD 6.3) and cropland (5.8 Mg C ha^{-1}, SD 4.3). The same pattern applied to species richness (Fig. 5c). Mean SOC of the forest (56.7 Mg C ha^{-1}, SD 18.7) was significantly higher than that of the woodland (37.9 Mg C ha^{-1}, SD 19.1), wooded grassland (37.3 Mg C ha^{-1}, SD 29.7) and cropland (36. Mg C ha^{-1}, SD 19.9) (Fig. 5b). Also, cropland had a significantly lower Shannon index (0.7, SD 0.5) than forest (1.5, SD 0.6), woodland (1.6, SD 0.4) and wooded grassland (1.2, SD 0.5) (Fig. 5d).

When analysing the data by DBH class and vegetation type, it was evident that the large trees (DBH > 60 cm) accounted for a large fraction of AGC in all vegetation types in comparison to a number of stems (Table 4). However, the contribution of the large trees to the total AGC was the greatest in forest and bushland.

3.3 Relationships between AGC, SOC and tree species diversity

The results of the correlation analysis between the different variables are shown in Fig. 6. The correlation between AGC and SOC was weak ($r = 0.170$) but statistically significant ($p < 0.05$) (Fig. 6a). There was a moderate correlation between AGC and species richness ($r = 0.475$, $p < 0.001$) (Fig. 6b) and between AGC and Shannon index ($r = 0.375$, $p < 0.001$) (Fig. 7d). However, the correlations between SOC and species richness (Fig. 6c) or between SOC and Shannon index (Fig. 6e) were not significant.

4. Discussion

The results of this study present carbon stocks and tree species diversity for a Guinean savannah landscape in Northern Sierra Leone. Therefore, the results do not provide a representative sample for the country's savannah biome, which comprises 25% of the country's vegetation area. However, the mean AGC in the landscape (29.4 Mg C ha^{-1}, SD 21.3) is comparable to that reported by Bouvet et al. (2018) for savannah and woodland landscapes in Sierra Leone (24.7 Mg ha^{-1}). In addition, Guinea (25.7 Mg ha^{-1}) and Ivory Coast (21.6 Mg ha^{-1}) had comparable mean densities to Sierra Leone while Ghana (14.7 Mg ha^{-1}) and Burkina Faso (8.5 Mg ha^{-1}) had lower densities according to the remote-sensing study of Bouvet et al. (2018). Relatively high AGC in the region could be attributed to high precipitation in the area (Sankaran et al. 2005) compared to other savannah and woodland landscapes in Africa. Mean AGC in the study area was similar to the Miombo woodlands in Tanzania (29.8 ± 13.1 Mg C ha^{-1}) (Ribeiro et al. 2013), but higher than the mean for woodlands in Taita Hills in Kenya (15.6 Mg C ha^{-1}) (Pellikka et al. 2018) and the dry Afromontane forest in Northern Ethiopia (19.3 ± 3.9 Mg C ha^{-1}) (Mokria et al. 2015).

Mean SOC in the study area (42.2 Mg C ha^{-1}, SD 20.6) was comparable to the Miombo woodlands (34.72 ± 17.93 Mg C ha^{-1}) (Ribeiro et al. 2013) but greater than in the Guinean savannah in Ghana (Djagbletey and Logah 2018) and Senegal's Sahel Transition Zone (Woomer et al. 2004). The increase in SOC is an indication of good soil properties and high precipitation in the landscape. High precipitation (Hijmans et al. 2005) and long-lasting precipitation (Gomez Paloma and Acs 2012) and high clay content (Jones 1973) positively affect SOC sink, while high disturbance (e.g. slash-and-burn farming, timber harvesting) had a negative influence on the SOC sink on the landscape (CILSS 2016).

The tree species richness in the landscape was high with *G. arborel*, *C. glutinosum*, *P. erinaceous* and *T. glaucescens* as the most abundance species. This is typical of West African Guinean savannah (Addo-Fordjour et al. 2009). Tree species richness is comparable to the Sudanian savannah (Dayamba et al. 2016) and the woodlands of Ngomakurira Mountain in Zimbabwe (Zimudzi et al. 2016) but higher than in the semi-arid and arid regions of southwestern Niger (Mahamane and Mahamane 2005). Anthropogenic activities (e.g. farming timber harvesting, wood collection) and wild fires are major drivers responsible for reduction in the species richness in the landscape. *P. erinaceous* (African rosewood) and *G. arborea* (Yamane) are among the widely harvested timber species by the local communities for domestic and commercial purposes. *G. arborea* was introduced to Sierra Leone from Thailand as part of a nationwide plantation forest programme established mainly in community lands (Savill and Fox 1967) and edges of protected forests (Anon. 1996). Although it was planted in specific areas, now *G. arborea* is visible in every part of the landscape because the seeds are dispersed by herbivores (e.g. cattle), spread fast and could be considered invasive.

The stem numbers in the landscape shows a J pattern by DBH class, indicating potential to regenerate due to the presence of many stems in the small diameter size classes (Zimudzi and Chapano 2016). Furthermore, high AGC was evident in few trees with large DBH class that contributed a significant proportion of the total AGC in the landscape. Also, the number of stems decreased with increasing DBH. The mean stem number was higher than in other savannah types, such as in Burkina Faso (Dayamba et al. 2016) and Miombo woodlands in the Eastern Arc Mountains in Tanzania (Shirima et al. 2011). This could be associated with the relatively high rainfall in the area (ca 2400 mm $year^{-1}$) compared to other savannah regions. The high proportion of stems in the lower DBH classes and the inverse J-shaped diameter distribution indicate regeneration (Chamshama et al. 2007, Nduwayezu et al. 2015) and support ecosystem productivity in the landscape. The low stocking of larger diameter tree classes could be associated mainly to the high rate of illegal timber harvesting and slash-and-burn farming in the region. Fire and unsustainable harvesting of non-timber forest products (NTFP) could also contribute to this pattern. Shannon diversity index was moderate at the landscape level, which implies the overall stability of the plant communities at the landscape level is moderate because plant community stability is known to be dependent on its diversity (Lhomme and Winkel 2002).

Forests are less influenced by fire than the woodland and wooded grassland but more targeted by farmers and timber harvesters because of their tree species composition and soil nutrients. Although seriously targeted, forests have the largest mean AGC in the landscape. Woodlands are less used for farming because of poor soil nutrients and hold the second-largest mean AGC. However, woodlands are also seriously threatened by logging as those are the main habitat for many tree species used for timber (e.g*. P. erinaceous)*. A few large trees were found to make a large contribution to AGC in bushlands and croplands. This could be associated with farmers practicing agroforestry during slash-and-burn farming or in their permanent farms. In this case, farmers keep some trees on the farm based on the value they have for them (e.g. provide fruits, shade and soil conservation). SOC showed significant differences among the vegetation types – forest showing the greatest mean SOC – which agrees with Akpa et al. (2016). High SOC in the forests could be associated with a high decomposition rate in forest soil because of low temperatures provided by overlocking canopies and high moisture, microbial activities and less disturbance from fire. Furthermore, most of the forests (gallery forest) are close to water bodies and have enough soil moisture for decomposition of dead biomass (Wang et al. 2012). Significant differences among the vegetation types were observed in terms of biodiversity, and forest, woodland and wooded grassland had higher species richness and Shannon index than other classes (bushland and cropland). This may, however, contribute to the high carbon content of these vegetation types.

Species richness showed very high linear correlation with Shannon diversity index. This implies that with increasing species richness, diversity (heterogeneity) also increases (Tramer 1969). Other significant relationships were between tree species diversity (both richness and Shannon index) and AGC, all showing a moderate positive relationship. It was clearly revealed that an increase in tree species diversity gives a corresponding increase in AGC in the studied landscape. This implies that ecosystem productivity (biomass) depends on biodiversity and total biomass depends on tree species richness and composition (Tilman et al. 1997) similar to some of the earlier studies (Strassburg et al. 2010b, Gamfeldt et al. 2013, Shirima et al. 2015, Mensah et al. 2016b).

The studied landscape had high carbon stock and tree species diversity (species richness and Shannon index). Therefore, robust management of the natural resources (forests) through community participation, especially in the Kuru Hills Forest Reserve, will improve ecosystem productivity and stability, which support carbon sequestration and storage in the landscape. Increasing forest cover, especially in the Kuru Hills, would increase water resources similarly as in the Taita Hills, Kenya, due to increased ability to capture atmospheric moisture and to store water resources in forested landscapes (Hohenthal et al. 2015, Cardwell 2017). Furthermore, the establishment and protection of community forests by government, communities and non-governmental organisations (NGOs) in this landscape will increase the area's ability to mitigate climate change through carbon sequestration. Finally, sustainable farming (e.g. agroforestry) and regulatory harvesting of ecosystem products by community members will decrease the release of carbon from the region.

5. Conclusion

The humid Guinean savannah in Northern Sierra Leone is a high carbon and biodiversity pool and contributes to global climate change mitigation through carbon sequestration and storage. Tree species diversity (biodiversity) moderately contributed to the high carbon stock in the landscape. Other factors such as precipitation and soil could be responsible for the increase in the soil carbon stock. Furthermore, the inverse J-shaped distribution of the stem numbers by DBH class demonstrates high regeneration that increase carbon in the landscape, which supports future climate change mitigation in the landscape. Forests and woodland are the most important pools for biodiversity and carbon. Management of these vegetation types together with the others will improve the biodiversity and carbon status of this region to benefit from REDD+. Sustainable farming (e.g. agroforestry), timber and pole harvesting, NTFP harvesting and fire management will reduce biodiversity and carbon loss in the landscape. Enforcing the management of protected forests and creating more community forests will increase carbon sequestration and biodiversity in the landscape with a contribution to global climate change mitigation.

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Figure captions

Figure 1. Location of the study area in Northern Sierra Leone, and clusters of the field plots (each cluster consist of ten plots) within the study area with the boundaries of the Kuru Hills Forest Reserve.

Figure 2. (a) Forest on the slopes of the Kuru Hills, (b) bushland with the Kuru Hills in the background, (c) woodland in the plateau, (d) wooded and partly burned grassland, (e) cropland and (f) Kuru Hills rising from the plateau covered by bushland. Note the smoke from the wildfires in the air. Photos by P. Pellikka, 2014.

Figure 3. Sample plot design with 0.1 ha plot and four 0.01 ha sub-plots.

Figure 4. The relative abundance (%) of the most common tree species in the landscape in terms of AGC and number of stems.

Figure 5. Comparison of (a) AGC, (b) SOC stock in the top 0–20 cm depth, (c) tree species richness and (d) Shannon index between vegetation types. Wooded gr. = wooded grassland.

Figure 6. The relationships of carbon stock and tree species diversity variables: (a) AGC vs. SOC, (b) tree species richness vs. AGC, (c) tree species richness vs. SOC, (d) Shannon index vs. AGC, (e) Shannon index vs. SOC and (f) species richness vs. Shannon index.

Table captions

Table 1. Vegetation types used for grouping the field plots.

Table 2. Variation in AGC, SOC at 0–20 cm depth, species richness and Shannon index at landscape-level (n = 160).

Table 3. Relative abundance (%) of stems, AGC and species in DBH classes.

Table 4. Relative abundance (%) of the large trees (DBH > 60 cm) in terms of stems and aboveground carbon (AGC) in different vegetation types.

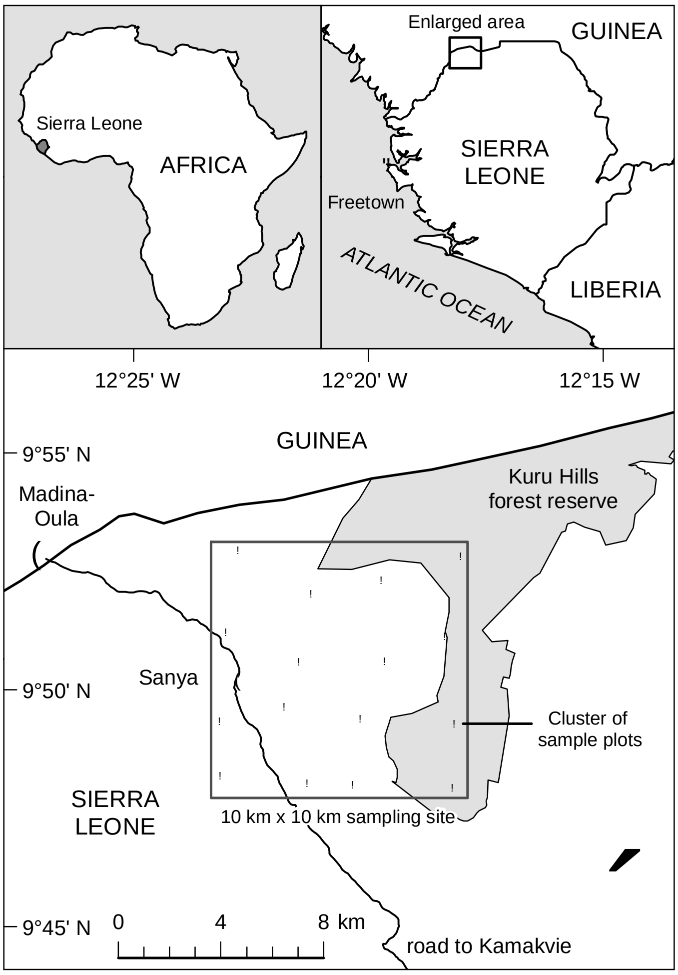
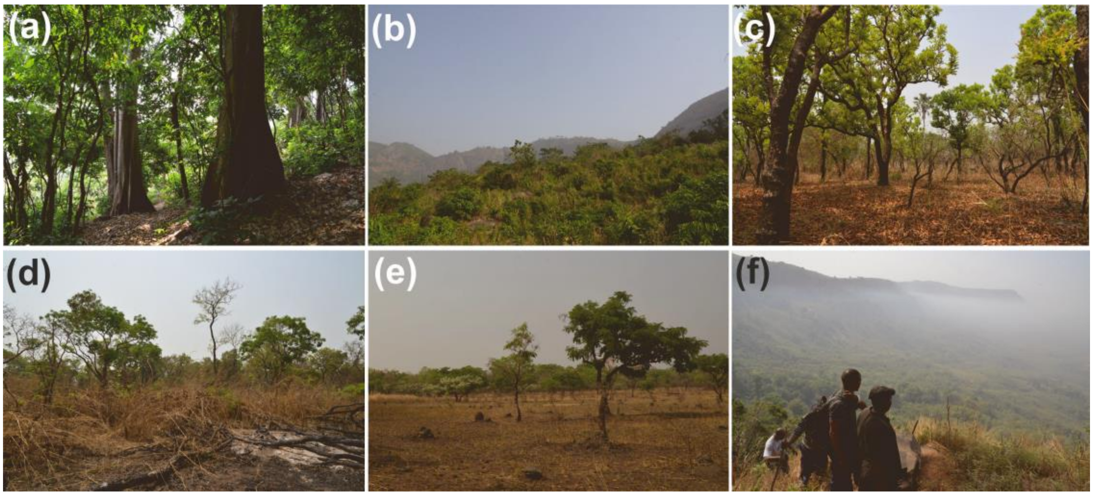


Figure 1. Study area and field plots with the boundaries of the Kuru Hills Forest Reserve in Northern Sierra Leone.



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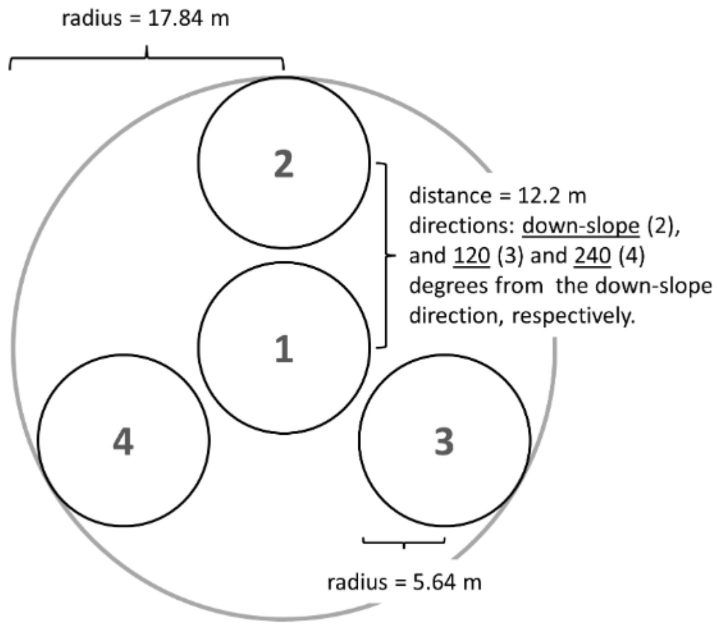

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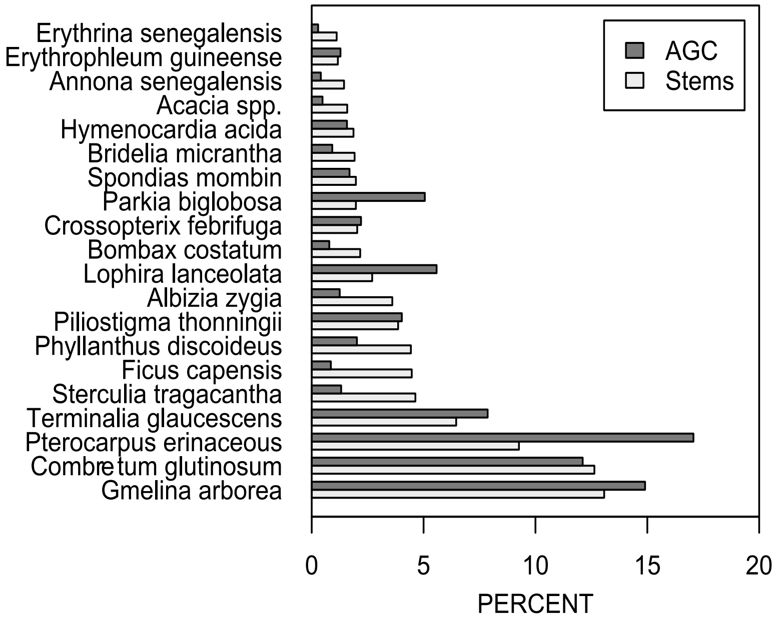

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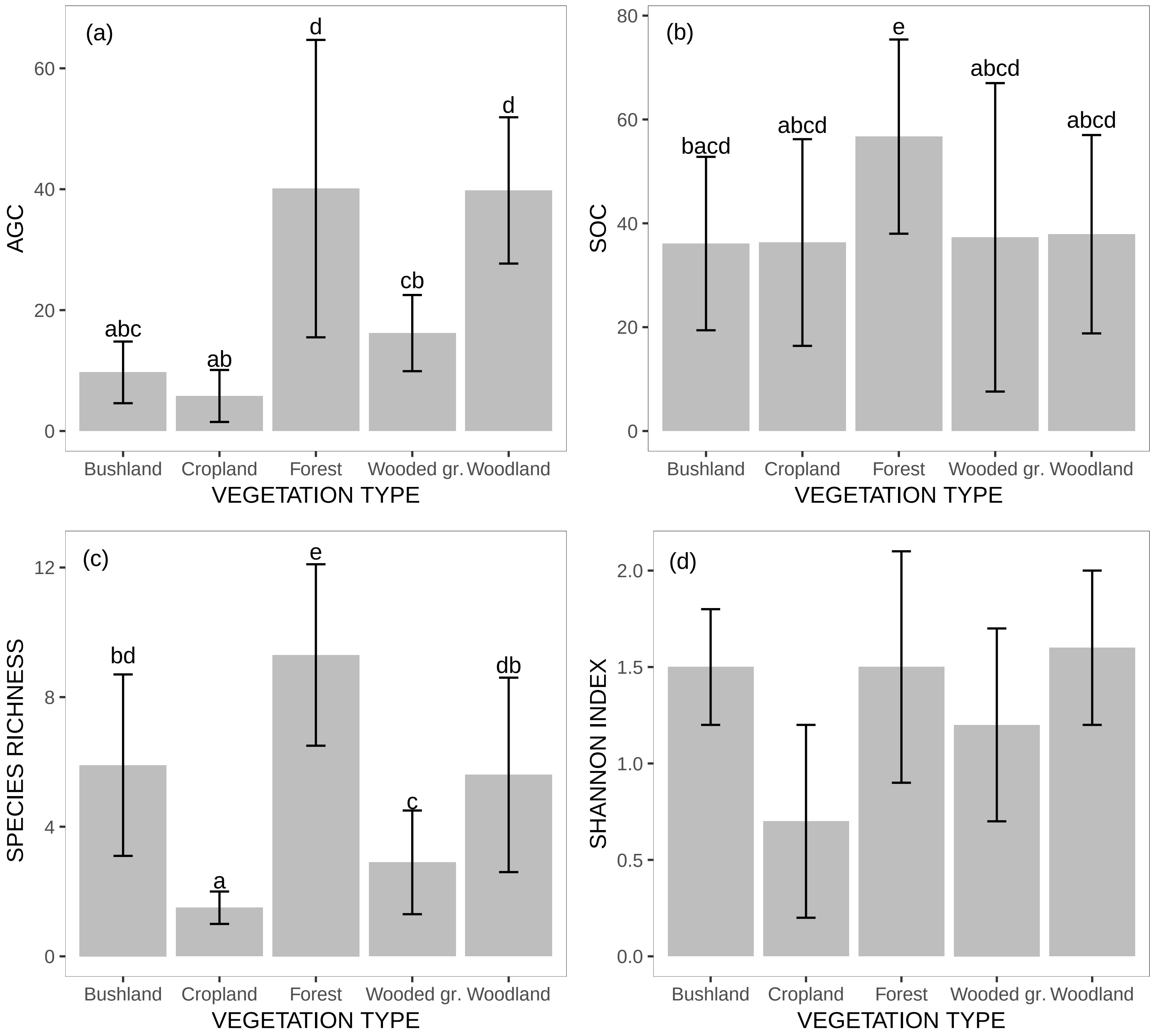

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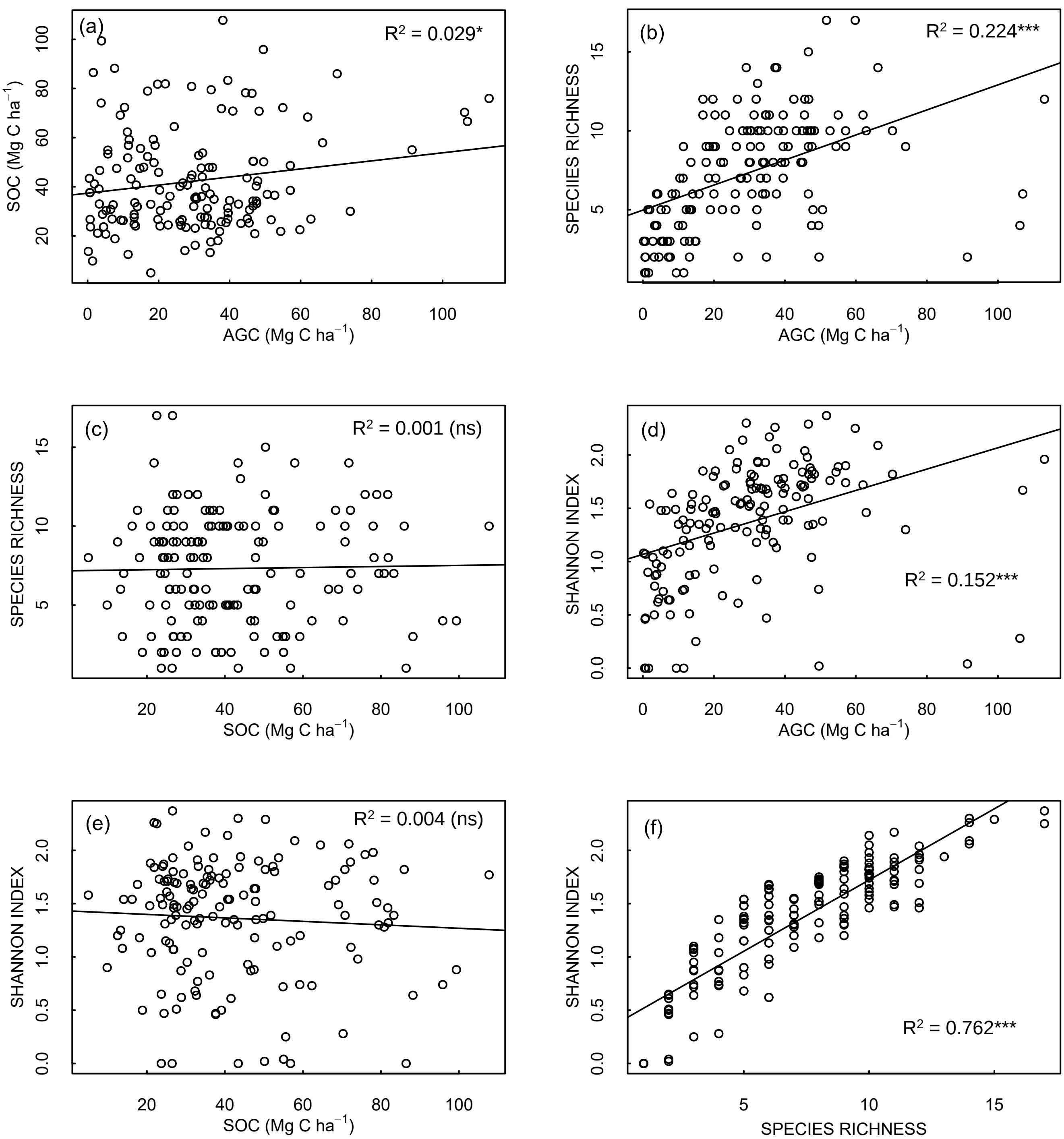

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Table 1. Vegetation types used for grouping the field plots.

Type	Description	Number of plots
Forest	A continuous stand of trees with crowns interlocking.	24
Woodland	An open stand of trees with canopy cover ≥ 40%. The field layer dominated by grasses.	66
Bushland	A mix of trees and shrubs with a canopy cover ≥ 40%.	13
Wooded grassland	Land covered with grasses and other herbs with woody vegetation covering 10–40 % of the ground.	29
Cropland	Cultivated land with annual or perennial crops.	28

Table 2. Variation in AGC, SOC at 0–20 cm depth, species richness and Shannon index at landscape-level (n = 160).

Variables	Min	Max	Mean	SD
AGC (Mg C ha^{-1})	0.2	113.0	29.4	21.3
SOC (Mg C ha^{-1})	4.9	107.2	42.2	20.6
Species richness	1	17	7	4
Shannon index	0	2.4	1.6	0.6

Table 3. Relative abundance (%) of stems, AGC and species in DBH classes.

DBH	Stems (%)	AGC (%)	Species (%)
4–10	63.0	1.1	17.1
10.1–20	23.0	18.8	21.2
20.1–30	8.2	24.9	19.2
30.1–40	3.6	21.9	13.5
40.1–50	1.4	13.8	13.9
50.1–60	0.5	7.8	7.8
> 60	0.4	11.7	7.3

Table 4. Relative abundance (%) of the large trees (DBH > 60 cm) in terms of stems and AGC in different vegetation types.

Vegetation type	Stems (%)	AGC (%)
Forest	0.32	12.3
Bushland	0.13	16.6
Woodland	0.38	8.5
Wooded grassland	0.07	5.6
Cropland	0.27	9.0