Aboveground Species Diversity and Carbon Stocks in Smallholder Coffee Agroforestry in the Highlands of Uganda

Namaalwa Justine, Balaba Susan Tumwebaze, Kigonya Ritah, and Gorettie Nabanoga

Abstract Types of agroforestry systems and their capacity to sequester carbon vary globally, and the extent of carbon sequestered greatly depends on environmental conditions and system management. This study aimed at investigating the species composition and determining the aboveground carbon stocks of coffee agroforests at low (1240–1320 m a.s.l.) and medium (1321–1504 m a.s.l.) elevations of Manafwa District in Uganda. For each elevation, the agroforest structures were described and the aboveground carbon (AGC) stocks estimated using allometric models for all measured shade and coffee trees. Two coffee varieties were cultivated with SL-14 extending up to 40 years, while LWIL-11, a more recently introduced variety, extended up to 7 years only. Therefore, the estimated AGC stocks were significantly greater for the SL-14 (0.250–2.317 tons ha^{-1}) than LWIL-11 (1.044–2.099 tons ha^{-1}) and were significantly higher at the medium versus the low elevation. The analysis for shade trees indicated no significant differences in the species diversity for the elevation sites, but with significant variations in mean DBH and thus AGC stocks. Farms at low elevation were characterized by smaller (2.037 ± 0.131 tCO2e ha^{-1}) and significantly high (2.037 ± 0.131 tCO2e ha^{-1}) mean AGC stocks per unit area for coffee and shade trees, respectively, as compared to the medium elevation farms. While the variation in the coffee trees within the elevation sites could be attributed to the uneven distribution within the age groups, the AGC stocks in the shade trees were attributed to the generally large sizes of the trees that dominated. Irrespective of the differences in elevation attributes, coffee agroforests can potentially provide carbon sinks and thus contribute to climate change mitigation.

Keywords Carbon sequestration · Coffee agroforest · Coffee-banana · Uganda

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1 Introduction

Climate change has been on top of the agenda for environment and development. Through efforts to enhance mitigation and adaptation to its negative effects, the role of forests is increasingly being recognized (Locatelli et al. 2010). This has been emphasized in several decisions by the United Nations Framework Convention on Climate Change (UNFCCC). Forests are a large sink of carbon (C), and their role in carbon cycles is well recognized (e.g., Dixon et al. 1994; Lorenz and Lal 2010). In order to enhance climate change mitigation, Uganda has in the past put much emphasis on natural and plantation forests. However, evidence is emerging that agroforestry systems are promising management practices to mitigate greenhouse gas emissions through increased aboveground and soil carbon stocks (Mutuo et al. 2005).

According to Pandey (2002), agroforestry systems are a better climate change mitigation option than oceanic and other terrestrial options. Agroforestry systems (with majorly tree-crop interactions) within the tropical latitudes have carbon storage potential in the multiple plant species and soil (e.g., Dixon 1995; Montagnini and Nair 2004). Dixon (1995) estimated the carbon storage potential at 12–228 Mg C ha^{-1}. In addition, agroforestry systems can have an indirect effect on carbon sequestration in reducing the pressure on natural forests (Soto-pinto et al. 2010), as Dixon (1995) estimated that 1 ha of sustainable agroforestry (with practices that minimize soil and plant disturbance) within the tropical latitudes could potentially offset 5–10 ha of deforestation. Agroforestry systems also have secondary environmental benefits such as helping to attain food security and secure land tenure in developing countries, increasing farm income, restoring and maintaining aboveground and belowground biodiversity, and providing corridors between protected forests. The systems have also been recognized to be of special importance because of their applicability in agricultural lands as well as in reforestation programs (Ruark et al. 2003).

Among the prominent agroforestry systems that have been recognized for sequestering carbon and contributing to climate change mitigation is the coffee agroforestry system. Soto-Pinto et al. (2010) indicated that these systems have emerged as promising land use systems for reducing or offsetting deforestation. As a result, shade-grown coffee systems have continued to be recognized as viable afforestation and reforestation strategies under the Clean Development Mechanism (CDM) of the Kyoto Protocol (Watson et al. 2000). However, to date, there have been few empirical, peer-reviewed investigations of carbon dynamics within coffee-forest landscapes (Schmitt-Harsh et al. 2012), and hence the potential for agroforestry as a strategy for carbon sequestration has not yet been fully recognized (Montagnini and Nair 2004). This is clear as several studies have indicated that more rigorous research results are required for agroforestry systems to be used in global agendas of carbon sequestration (Oelbermann et al. 2004; Ramachandran Nair et al. 2010). Albrecht and Kandji (2003) also emphasized that the significance of agroforestry with regard to carbon sequestration and other CO2 mitigating effects is being widely recognized, but there is paucity of quantitative data on specific systems which may include crops integrated with remnant trees or crops integrated in planted trees.

Coffee agroforests are a common system in Uganda where coffee is the major cash crop for the country. Coffee is traditionally grown under the shade of trees, forming coffee agroforests. Although this system has been reported to have the potential of contributing to climate change mitigation through carbon sequestration (e.g., Mutuo et al. 2005; Ramachandran Nair et al. 2010; Soto-Pinto et al. 2010; Schmitt-Harsh et al. 2012), there are limited studies about the subject in Uganda. Available studies have focused on (1) carbon stocks in agroecosystems (Mukadasi et al. 2007; Gwali et al. 2015; Kyarikunda et al. 2017; Kabiru et al. 2018), (2) carbon payments and their role in tree diversity and carbon stocks (Nakakaawa et al. 2010), and (3) soil organic carbon stocks under coffee agroforestry systems (Tumwebaze and Byakagaba 2016). ICRAF (International Centre for Research in Agroforestry) and its collaborators concluded that the greatest potential for carbon sequestration in the humid tropics is aboveground, not in the soil (Montagnini and Nair 2004). This chapter evaluates the aboveground carbon (AGC) stocks for the coffee agroforestry system in Manafwa District, Uganda. The main objective of the study was to determine the AGC storage levels for coffee agroforests at two different elevations.

The results are expected to inform project proponents interested in promoting shade trees in the region (and thus link coffee farmers to voluntary carbon markets) about the desirable tree species for carbon sequestration. As Luedeling et al. (2011) put it, studies on the C sequestration potential of agroforestry are often conducted with a view to creating opportunities for smallholder farmers to benefit from international carbon payment schemes. The findings may also inform the development and implementation of the National REDD+ strategy in which agroforestry is expected to contribute to the enhancement of forest carbon stocks. Evaluating the carbon storage capacity of coffee agroforestry systems with different shade tree species will further contribute to a better understanding of the role that these ecosystems can play in REDD+ programs.

2 Study Area

Arabica coffee is grown in the highland areas of the country including the slopes of Mount Elgon in the Eastern part of Uganda. The investigation was undertaken in Manafwa District located on the slopes of Mount Elgon. It is located at coordinates 0°53 North and 34°20 East, bordered by Bududa District in the North, Mbale District in the West, Tororo District in the South, and Kenya in the East. The district occupies a total surface area of 602.1 sq. km and is divided into three topographic regions including the lowland with 1300–1500 m a.s.l., the upland with 1500–1600 m a.s.l., and the mountainous landscapes above 1600 m a.s.l. (Mugagga 2017). The district lies within the mixed montane forest zonal belt, below an elevation of 2500 m a.s.l.

(Scott 1994). The district experiences a bimodal rainfall pattern, with the heaviest rains being in the first season of March–June and the second season in September–November. The area receives a mean annual rainfall of 1500 mm, with mean maximum and minimum temperatures of 23° and 15°, respectively (Mugagga et al. 2012). The volcanic soils are fertile and rich in calcium, sodium, and potassium (Mugagga et al. 2010).

The district is dominated by small-scale farmers, and it is among the five major districts growing Arabica coffee on the slopes of Mt. Elgon, the others being Bududa, Bulambuli, Mbale, and Sironko (MWE 2015). Arabica coffee varieties grown in the area include SL-14, SL-28, and Nyasaland (Liebig et al. 2018), as well as LWIL-11 which was reportedly introduced in 2010. The coffee is predominantly cultivated under the coffee-banana system with integration of other crops such as maize, sorghum, potatoes, and beans (Kimaiyo et al. 2017). Planting additional crops and adding shade in the coffee systems are adaptation strategies used by the local farmers to mitigate the effects of climate variabilities such as droughts and pest and disease infestation in the coffee farms, as well as to obtain short-term benefits like food and income (Mugagga 2017).

3 Data

3.1 Data Collection Methods

A total of 16 coffee agroforest sites were investigated and categorized based on the major coffee variety grown and elevation. The structure for each site was described in terms of the variety and age of coffee and the tree sizes and composition of the shade trees. The two coffee varieties, that is, LWIL-11 and SL-14, have been introduced in the area at different times, with LWIL-11 as the most recent variety. Within each variety, coffee plants at different (currently available) ages were considered. For each of the 16 farms, a random point was established, and an area ranging from 1 to 2.5 ha was mapped off using a GPS. In this area (total inventory area of 24.5 ha), all the shade trees (≥10cm) and saplings (3–9.9 cm) were enumerated for diameter at breast height (DBH), total height and crown diameter, and the species identified. Within the inventoried area for each site, 600 m^2 (20*30 m) rectangular plots were randomly established targeting five plots per hectare. In each plot, stump diameter for each coffee plant was measured at 5–10 cm from the ground (depending on the forking point) and the number of forks (for the forked crop) counted. Fork diameter was measured at 10 cm after forking point for utmost three forks per plant. The crown diameter and crop height were measured for each of the coffee stand using a measuring rod calibrated in meters. A total of 15 plots were established for each of the LWIL-II and SL-14 varieties.

3.2 Data Analysis

The analysis was done to identify differences in the plant species composition and thus carbon sequestration levels for coffee agroforests at 1240–1320 m a.s.l. (low elevation) and 1321–1504 m a.s.l. (medium elevation). For each cluster, the agroforest structures (tree sizes and composition) were described, and the Above Ground Biomass (AGB) and carbon stocks were estimated. The differences were then sought between the clusters. The agroforest structure was defined through descriptive statistics of the key parameters including DBH, height, dominant species, and species diversity for the shade trees as well as the variety and age of coffee plants. For all the measured shade trees and coffee trees, allometric models were used to estimate the AGB and carbon stocks. For all trees, saplings, and coffee trees, the estimated biomass (tons/ha) was used to derive the carbon sequestration potential using the IPCC defaults where carbon is estimated to be a constant proportion (0.47) of live and standing biomass (IPCC 2006).

For the coffee plants, within each variety, the stands were clustered in age groups with a 2-year interval, the minimum being 1–3 years and maximum >30 years. But this took consideration of the fact that the highest class for LWIL-11 was 4–6 years, while SL-14 has up to 13–15 years, with only one farm in the category of 40 years. The mean stump diameters for the coffee trees of different varieties but the same age group and/or elevation were compared.

The AGB for coffee plants was derived using an allometric biomass model developed by Tumwebaze and Byakagaba (2016). The model is as specified below:

$$\mathrm{Ln}(\mathrm{AGB}) = -1.553 + 0.86\mathrm{Ln}(\mathrm{SD}) + 0.20\mathrm{Ln}(\mathrm{HT}) + 0.47\mathrm{Ln}(\mathrm{CD}) + 0.21\mathrm{Ln}(\mathrm{BA})$$

where:

AGB = aboveground biomass in kg
SD = stump diameter in cm at 15 cm from the ground
HT = shrub height in m
CD = crown width in m
BA = basal area in m^2

The estimated biomass was corrected using the Baskerville (1972) correction factor (1.082) to remove the biasness of antilog of biomass.

For the shade trees, descriptive statistics of the key parameters including DBH and height were generated. Further, species diversity was assessed and the Shannon-Wiener index of diversity was used, designated as:

$$H' = \sum p_i \log p_i$$

where:

H' = Shannon index of diversity
$\sum$ = summation of values for s species

p_i = the proportion of individuals or the abundance of species I in the sample
$\log_a$ = base of any logarithm

The differences in the mean DBH values for tree species occurring at both low and mean elevation were investigated using a t-test.

In order to estimate AGB and thus carbo stocks, the revised nondestructive allometric equation described by Chave et al. (2014) was used to estimate the aboveground live biomass (AGB, kg) contained within each tree, given as a function of DBH (cm), height (H, m), and wood-specific gravity (ρ, g cm^{-3}):

$$\text{AGB} = 0.0673^{*}\left(D^2 H \rho\right)^{0.976}$$

Wood density values were obtained from the National Biomass Survey (NBS) data base and the study by Buyinza et al. (2014). The estimated AGC values for the coffee and tree components of the agroforests in low and medium elevation were compared using descriptive statistics.

4 Results

The coffee agroforests in Uganda are mainly established through integrating coffee and other crops mainly bananas in a landscape with remnant trees. Low elevation was characterized by a mean value of 1291 ± 9.68 m a.s.l, while medium elevation was characterized by a mean value of 1357 ± 21.12 m a.s.l. In terms of composition, the farms at the low elevation were mainly coffee-banana systems with remnant trees (mainly the large trees with expanse crowns), while at the medium elevation, most of the farms had coffee integrated with remnant trees and less of crops. The estimates of the tree components of the system are presented first separately duly considering the effect of elevation. The estimates are then combined to reflect the biomass and carbon stocks for the low/medium elevation agroforest systems.

4.1 The AGB and Carbon Stocks for Coffee

The enumerated coffee plants ranged between 1 and 5 years for LWIL-11 and 1 and 40 years for SL-14. The management of the agroforestry farms, and specifically the coffee plants, was not uniform; and as a result, there were variations in the stump diameters of plants of the same variety and age. Within each variety, the stands were further clustered into age groups of a 2-year interval, and the stump diameters varied between 2.79 ± 0.91 and 2.93 ± 0.86 cm for LWIL-11 and 1.73 ± 0.42 and 6.065 ± 2.08 cm for SL-14. The descriptive statistics for the carbon sequestered by the coffee plants of different varieties and age and grown at different elevations is presented in Table 1.

Table 1 Descriptive statistics for carbon sequestered by coffee plants (tons/ha)

Coffee variety	Elevation	Age range	Mean	Standard error	Minimum	Maximum
LWIL-11	Low	4–6	1.044	0.169	0.711	1.262
	Medium	1–3	1.315	0.251	0.604	2.774
		4–6	2.099	0.104	1.944	2.297
SL-14	Low	1–3	0.250			
		7–9	2.198	0.816	1.296	3.827
		10–12	0.729			
		13–15	0.930	0.001	0.929	0.930
	Medium	4–6	2.301	0.206	1.868	2.821
		7–9	2.317	0.667	1.650	2.984
		>30	1.462			

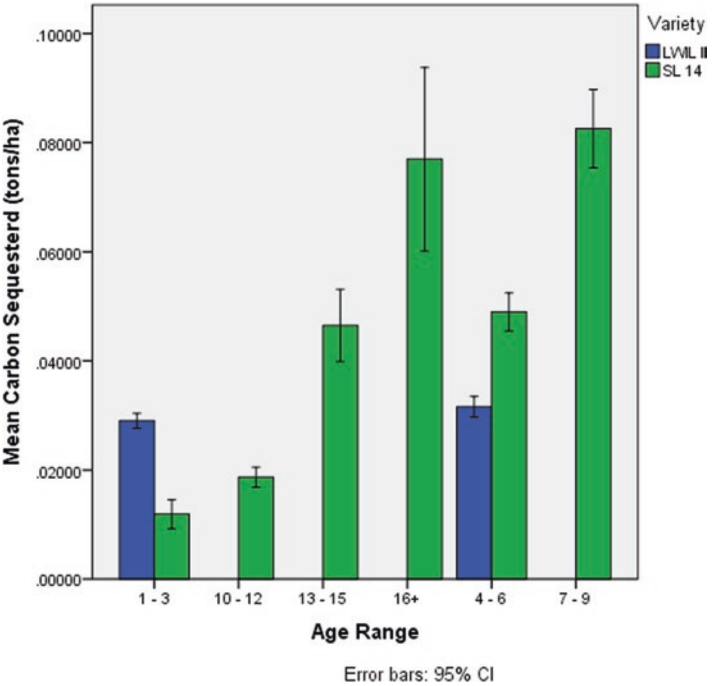

Fig. 1 Mean carbon content of coffee plants across different age classes

Despite the uneven representation of coffee plants in the different age groups for the different varieties, it was observed that SL-14 had generally higher C stocks in the comparable age group of 4–6 years under medium elevation. The analysis of variance for carbon stocks revealed a significant interaction ($p = <0.001$) between age range and variety, implying that the amount of carbon sequestered for each variety of coffee depends on the age of the plant (Fig. 1). There were, however, a nonsignificant ($P = 0.776$) difference among slopes and nonsignificant ($P = 0.112$) interaction between slope and variety.

4.2 The Shade Trees

Twenty-seven shade tree species were identified in the landscape, including *Cordia millenii*, *Ficus natalensis*, *Albizia coriaria*, *Ficus sur*, *Terminalia glaucescens*, *Combretum collinum*, and *Rhus vulgaris.* While there were some similar species in both the low and medium elevation sites, there were characteristic species that were found exclusively in the medium slope sites, such as *Combretum collinum, Acacia* spp., and *Lannea barteri* (Table 2). These were indicative of a wooded savannah vegetation that was selectively cleared to establish coffee. The species diversity index revealed mean values of 1.493 ± 0.368 and 1.722 ± 0.472 for the low and medium elevation sites, respectively, with no statistical difference between the mean values ($t = -1.055$; $p = 0.309$; df = 14).

Table 2 Proportion (%) of different species and estimated mean biomass for the shade trees

	Species composition and biomass estimates					
	Low elevation			Medium elevation		
Species	Proportion (%)	Mean (±SD) DBH (cm)	Mean biomass (tons/tree)	Proportion (%)	Mean (±SD) DBH (cm)	Mean biomass (tons/tree)
Albizia spp.	20.4	29.91 ± 20.71	0.745	4.91	22.65 ± 10.05	0.211
Ficus natalensis	19.4	24.67 ± 11.66	0.259	12.38	20.55 ± 9.09	0.172
Cordia millenii	17.0	33.41 ± 13.39	0.831	16.67	18.39 ± 7.70	0.190
Ficus spp.	13.5	43.77 ± 22.38	1.124	5.43	30.56 ± 29.62	0.736
Grevillea robusta	9.7	26.20 ± 11.90	0.439	4.13	16.82 ± 4.57	0.118
Maesopsis eminii	6.8	23.02 ± 8.02	0.246	1.57	28.65 ± 11.08	0.315
Persea americana	4.7	22.79 ± 6.38	0.181	1.04	12.08 ± 3.23	0.030
Terminalia glaucescens				13	15.37 ± 5.20	0.084
Combretum spp.				10	16.08 ± 4.88	0.087
Acacia spp.				7	24.13 ± 8.71	0.273
Croton megalocarpus				5	11.93 ± 1.97	0.043
Lannea barteri				2	13.95 ± 7.43	0.053

The mean DBH for the trees in the low elevation sites was 32.29 ± 2.07 as compared to 19.22 ± 1.323 for the trees in the medium elevation sites. A pairwise comparison test was conducted, and it revealed a mean difference of 11.838 ± 1.490 ($p = 0.000$). For both sites, the high diameter classes were dominated by *Cordia millenii* and *Ficus* spp. which were also the predominant species in this landscape. The DBH for *Ficus* spp. varied between 13.5 and 99.5 cm, with a mean of 44.6 cm, while for *Cordia millenii* varied between 10 and 58.8 cm, with a mean of 25.9 cm. Species dominance within the landscape and biomass estimates is presented in Table 2.

For the species that occurred predominantly at both elevations, the mean DBH values were generally higher for the trees found at low elevation. A pairwise comparison test revealed statistical differences between the mean values ($t = 2.956$; $p = 0.012$; df = 6). The high occurrence of the large diameter species in the low elevation sites as compared to the medium elevation sites explains significant differences in mean biomass stocks. The AGB for shade trees varied between 0.0034 tons/tree (*Lannea barteri*) and 4.205 tons/tree (*Ficus sur*).

4.3 Aggregated Attributes for the Coffee Agroforestry System at Different Elevations

The attributes of the system components indicated that the biomass for coffee plants was approximately two orders of magnitude smaller than that for shade trees with mean values varying between 1.044 and 2.099 tons ha^{-1} for LWIL-II and 0.250 and 2.317 tons ha^{-1} for SL14 depending on the age class and elevation. The amount of carbon sequestered varied widely across the sites within the low and medium elevation (Table 3).

Farms at low elevation were characterized by smaller AGC stocks per unit area of coffee, but with significantly high AGC stocks per unit area of shade trees. While the variation in the coffee trees within a given subsystem (low/medium elevation) could be attributed to the uneven distribution within the age groups, the AGC stocks in the shade trees were attributed to the characteristics (species and sizes) of the trees that dominated the subsystem. The mean aboveground carbon stored at the time the measurements were taken was 42.01 tons ha^{-1} and 12.48 tons ha^{-1} at the low and medium elevation farms, respectively.

5 Discussion

Coffee agroforests have a great potential to sequester carbon and thus contribute to climate change mitigation. However, the amount of carbon sequestered varies with the site- and system-specific characteristics, mainly elevation and tree characteristics, especially size. The farms at the low elevation were mainly the coffee-banana

Table 3 Summary statistics for coffee agroforestry systems in the low and medium elevation

	Sites	
	Low elevation	Medium elevation
Coffee plants per ha		
LWIL-11	1091	970
SL-14	494	570
Shade trees		
Species count	19	29
Mean tree count/ha	38 ± 23.9	35 ± 13.98
Species diversity	1.493 ± 0.368	1.722 ± 0.472
Mean Dbh (cm)	31.34 ± 8.66	17.76 ± 5.80
Mean height (m)	12.93 ± 1.56	8.35 ± 2.60
Mean CO2e (tons ha^{-1})		
Trees	39.98 ± 13.98	10.03 ± 1.59
Coffee trees		
LWIL-11	1.898 ± 0.117	2.233 ± 0.047
SL-14	2.177 ± 0.144	2.679 ± 0.162
Overall	2.037 ± 0.1305	2.456 ± 0.104

systems with large diameter remnant trees and relatively lower species diversity as compared to the sites at the medium elevation. Farms located at the medium elevation were mainly composed of coffee and trees, with less of banana and other crops integrated.

The coffee species grown in the area were not distinct by elevation but rather by preferences and access to planting material, and thus no defined distribution pattern across the two elevations. The variety LWIL-11 is more recently introduced in the area, dating back to the year 2010. Therefore, the analysis for carbon stocks in coffee plants was more interesting in relation to age groups across a given variety as indicated in Table 2. Given the variations in the management practices, there was no clear pattern on the rate of carbon accumulation in the coffee plants with increasing age.

While in some instances the species for the shade trees were similar for both low and medium elevation sites, the maximum attained diameter and height varied and thus the carbon stocks. While tree species such as *Cordia millenii*, *Ficus* species, and *Albizia* spp. were identified at both elevations, savannah species such as *Combretum*, *Acacia*, *Rhus vulgaris*, and *Lannea barteri* were identified in the medium elevation farms. The test for species diversity confirmed significant differences, which pronounces the inherent differences in carbon accumulation levels over time. While the coffee trees have greatest C stocks at the medium elevation, shade trees in the low elevation have more C stocks as compared to the medium elevation trees. Some previous studies have highlighted the significance of the large diameter trees in agroforestry systems. For example, Ehrenbergerová et al. (2016) reported AGB of shade trees varying between 9.9 kg (*Erythrina edulis*) and 18,400 kg (*Carinian adecandra*) per tree (DBH ≥ 10 cm). Manjunatha et al. (2017) clearly showed the contribution of dominant tree species of coffee-based agroforestry systems with regard to carbon stocks.

Considering the system as a whole rather than the individual tree components, mean AGC stocks of 42.01 tons ha^{-1} and 12.48 tons ha^{-1} for the agroforests in the low and medium elevation, respectively, were estimated. Schroeder (1994) estimated average carbon of 21 and 50 Mg C ha^{-1} for agroforestry systems in subhumid and humid regions. This clearly indicates the variations with respect to elevation, implying that elevation has an effect on the productivity of vegetation and thus biomass stocks. Girardin et al. (2010) stated that AGC in tropical forests typically decreases with elevation, due to temperature and productivity gradients. Therefore, site-specific characteristics are important to consider when estimating the existing or likely contribution of forestry systems to climate change mitigation. Further, while this study focused on AGC stocks only, Tumwebaze and Byakagaba (2016) reported that soil carbon accumulation in coffee stands is far much higher than aboveground carbon. This affirms the role coffee agroforests can play in storing carbon, most especially when all carbon pools are considered.

6 Conclusions

Coffee agroforests have a great potential to sequester carbon and thus contribute to climate change mitigation. However, the amount of carbon sequestered varies with the site- and system-specific characteristics, mainly elevation and tree characteristics. Despite the identified differences in the shade tree characteristics at the low and medium elevation sites, the potential of the agroforest systems at the varying elevations to sequester carbon needs to be recognized. This would be as important as is often reported for either the low and highly stocked tropical forests or the natural forests and woodland forests. While it is evident that different coffee varieties in the Mt. Elgon are either grown as a monocrop or with shade from tree species or bananas, it is important to appreciate the contribution of shade trees in carbon sequestration and thus mitigation of climate change. And thus, as Uganda continues to prepare and implement its National REDD+ strategy, agroforestry systems need to be considered as important carbon sinks, especially in cases where remnant trees exist or/and integration of trees on farmlands has been/can be implemented. However, the capacity of different tree species to sequester carbon needs to be considered against the benefits the different tree species yield to the system, such as provision of shade and litter.

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