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*Correspondence:

Lisa Elena Fuchs
L.Fuchs@cgiar.org

†ORCID:

Lisa Elena Fuchs
orcid.org/0000-0002-8342-6087
Levi Orero
orcid.org/0000-0003-0071-8592
Shem Kuyah
orcid.org/0000-0001-7692-585X
Henry Neufeldt
orcid.org/0000-0002-0880-9395

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Lisa Elena Fuchs^{1*†}, Levi Orero^{1†}, Stephen Ngoima², Shem Kuyah^{2†} and Henry Neufeldt^{1,3†}

¹ International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenya, ² Department of Botany, Jomo Kenyatta University of Agriculture and Technology (JKUAT), Nairobi, Kenya, ³ United Nations Environment Programme (UNEP) Technical University of Denmark (DTU) Partnership, Copenhagen, Denmark

Agroforestry has potential to address the adverse effects of climate change through carbon sequestration, increasing biodiversity and improving adaptive capacity and resilience among smallholder farmers. However, this potential is context specific and insufficiently quantified in smallholder farming systems, partly because of inherent variability of smallholder farms. Our study aimed to determine the tree/shrub diversity and carbon stocks in different agroforestry systems within smallholder farms in two 100 km² sites, the so-called lower and middle Nyando sites, in western Kenya. In both, context-specific agroforestry adoption had been promoted among households of four community associations through an asset-based community development (ABCD) approach. Their farms were assessed and compared with those of relevant comparison samples. Trees and shrubs were inventoried on a total of 106 farms, and their formations classified in five major agroforestry practices: hedgerows, multipurpose trees on farm (MPT), riparian buffers, woodlots, and boundary planting. To assess above-ground biomass (AGB) of individual trees/shrubs, diameter at breast height measurements were taken. Strong regional differences were considered in data analysis and presentation. Altogether, 3,353 and 6,346 trees/shrubs were inventoried in the lower and middle Nyando sites, respectively. AGB was significantly higher in middle than in lower Nyando. Woodlots had the highest amount of AGB carbon stock, while MPT had the highest diversity of tree/shrub species in all the groups. Conversely, boundary planting had the highest number of trees/shrubs inventoried and hence was the most common agroforestry practice across all the samples in both regions. Dominant AGB contributor species were *Grevillea robusta* (37.8%) in middle, and *Eurphobia tirucalli* (16.5%) in lower Nyando. This study provides empirical evidence that asset-based and community-driven selection and implementation of both tree/shrub species and agroforestry practices can contribute positively to species and practice diversity, which are associated with AGB carbon stock levels and wider agro-ecosystem diversity. This study hence provides

benchmark information that is relevant for SDG goal 15 on “life on land,” and various specific targets, and can inform sustainable establishment of carbon sink facilities by supporting smallholders to uptake contextually suitable and economically sensible agroforestry practices in an overall effort to foster and support sustainable development.

Keywords: asset-based community development, agroforestry, above-ground biomass, carbon stocks, smallholder carbon, nationally determined contributions, multipurpose trees

INTRODUCTION

Efforts to combat climate change in the agriculture, forestry, and other land use (AFOLU) sectors hinge on reducing greenhouse gas emissions and increasing carbon sequestration in all land use systems, including agroforestry. Agroforestry is among the most promising land use strategies to mitigate climate change through carbon sequestration while helping rural communities improve their livelihoods and adapt to a changing climate (Thorlakson and Neufeldt, 2012; Ranjitkar et al., 2016; Quandt et al., 2017). Trees planted in crop and in pasture fields contribute to climate change mitigation by binding carbon in biomass and by raising soil organic carbon levels. A 2016 assessment showed that 43% of all agricultural land globally had at least 10% tree cover in 2010 (Zomer et al., 2016). The same study also illustrated that in many developing countries, there are large unproductive croplands and land considered as degraded that could be transformed into productive agroforestry systems. Whereas the positive role of agroforestry in climate change mitigation is recognized in the scientific literature and global land restoration debates (Thorlakson and Neufeldt, 2012; Ranjitkar et al., 2016; Quandt et al., 2017), the role of smallholder agroforestry systems has remained insufficiently explored. Better knowledge about their contribution to climate change mitigation can contribute to focus support and priorities on good land use practices to enhance climate change adaptation and mitigation in developing countries and contribute significantly to SDG goal 15 on “life on land,” and various specific targets, including 15.1, 15.2, 15.3, 15.5, 15.9, in eastern Africa specifically, and contributes to 15.a and 15.b. The study also interacts with goals 1, 2, 5, 8, 13, 16, and 17.

Agroforestry has been recognized as a suitable land use system in fragile areas and smallholder systems because of its potential to diversify and sustain production for increased social, economic and environmental benefits when compared with treeless alternatives (Roshetko et al., 2006). These systems maintain high tree densities and may contain high carbon stocks. When combined with crops and pasture, trees and shrubs can increase food and feed production locally, creating a positive impact on food security (Thorlakson and Neufeldt, 2012; Franzel et al., 2014; Sileshi et al., 2014; Quandt et al., 2017). When used on degraded lands, woody perennials offer potential for increased carbon stocks because of increased biomass production, and have a positive impact on biodiversity (Chazdon, 2008). Increasing living biomass in agricultural landscapes can reduce pests (Pumari et al., 2015), and may increase crop production because of the impacts of trees on soil fertility, soil moisture, soil nutrients, wind speed and microclimate (Kuyah et al., 2016). The role of agroforestry in enhancement of biodiversity underpins

the provision of these ecosystem services (Kuyah et al., 2016). Trees are often conserved on farms through selectively retaining trees or shrubs in crop or pasture fields or planting new naturally occurring ones, a practice that is recognized as farmer-managed natural regeneration (FMNR) (Garrity et al., 2010; Haglund et al., 2011; Weston et al., 2015; Reij and Garrity, 2016). These trees provide benefits that would otherwise be sourced from the forest, reducing pressure on forests and creating habitats for different flora and fauna on agricultural lands (McNeely and Schroth, 2006).

Scientific evidence shows that agroforestry systems have a large potential for climate protection (Zomer et al., 2016). Globally, agricultural lands with trees stock an average of 21.4 Mg ha⁻¹ of carbon stocks in biomass. In western Kenya, two studies estimated carbon in agroforestry systems to be 17 Mg ha⁻¹ in aboveground biomass (Kuyah et al., 2012a) and 5 Mg ha⁻¹ in belowground biomass (Kuyah et al., 2012b), totaling 22 Mg ha⁻¹ of carbon in living biomass. Because of high biomass, agroforestry systems can store more carbon compared to crop and pasture fields without trees (Nair, 1993; Budiadi and Ishii, 2010). However, the amount stored is context specific and varies depending on factors such as agroforestry practice, type of species, age of agroforestry system, management influence, and environmental conditions (Luedeling et al., 2011; Kuyah et al., 2014). Yet, methodological challenges such as lack of standardized methods and limited number of allometric biomass equations render it difficult to accurately estimate carbon stocks in agroforestry systems (Sileshi et al., 2014). This is partly due to difficulties associated with biomass assessment in smallholder systems, which are highly heterogeneous (Kuyah et al., 2012a). For instance, the overall carbon sink potential is insufficiently quantified with respect to specific agroforestry practices. Furthermore, Rosenstock et al. (2019) showed that the absence of standardized tools to report on agroforestry has led to it often not being included in measurement, reporting and verification systems under the UNFCCC. This leads to agroforestry not being considered in many developing countries' achievements toward reaching their Nationally Determined Contributions (NDCs) despite them explicitly mentioning agroforestry as priority activity (Rosenstock et al., 2019). This has important implications, specifically for the quantification of smallholder systems' contribution to developing countries' NDCs and the counting of smallholder agroforestry carbon toward global targets. These limitations have led to lack of data, varying conclusions, and a fragmented understanding of the role of agroforestry in climate change and development.

Most smallholder farming systems in Kenya pursue conventional agricultural intensification, which has contributed

to greenhouse gas emissions, soil degradation and loss of biodiversity. This challenge has spurred increased interest in sustainable intensification, and the potential of agroforestry systems to couple agricultural production, carbon sequestration and biodiversity conservation. Agroforestry also provides opportunities for smallholder farmers to benefit from existing and emerging opportunities in carbon markets (Roshetko et al., 2006; Seeberg-Elverfeldt et al., 2009). While the multifaceted positive roles agroforestry can play have been widely documented, the contribution that individual agroforestry practices can make has received little attention in previous studies. Compared to carbon storage potential of different tree species that has been identified for various regions on the African continent (Brown, 1997; Ketterings et al., 2001; Zewdie et al., 2009; Kuyah et al., 2012a, 2014; Mugasha et al., 2013; Negash et al., 2013; Mokria et al., 2018), the carbon storage potential of different agroforestry practices in western Kenya has not been explored in detail. The objective of this study was to determine the effects of agroforestry promotion through the implementation of an asset-based community-driven development (ABCD) pilot project in western Kenya, which promoted asset-based, community-selected, and context-specific climate-smart agricultural practices, including selected agroforestry practices, on the diversity of tree and shrub species and carbon stocks in general, and on carbon stocks in selected agroforestry practices and tree and shrub species in particular. By providing insights into the diversity of tree species and carbon stored in different agroforestry practices, this study provides benchmark information that can allow various actors to promote evidence-based and sustainable establishment of carbon sink facilities by supporting smallholders to uptake the most suitable and economical agroforestry practices in a given area in an overall effort to support sustainable community development.

METHODOLOGY

Study Site

The study was conducted in two 10 km by 10 km benchmark sites along the Nyando River basin in western Kenya (Figure 1). The so-called lower and middle Nyando “blocks” are sentinel research sites that were initially defined in the context of the Western Kenya Integrated Ecosystem Management Project (WKIEMP). The project identified these sites along the three major rivers in western Kenya, Rivers Nzoia, Yala, and Nyando, and collected comprehensive social, economic and biophysical data in three sites along each of these rivers (Verchot et al., 2008). Within these sites, the World Agroforestry Centre (ICRAF), in collaboration with the Coady International Institute, implemented an ABCD pilot project between 2010 and 2014. The ABCD approach to international development, drawing on earlier works focusing on the empowerment of marginalized groups and areas in urban inner cities of the United States (Kretzmann and McKnight, 1993), was comprehensively adapted for the international development context by the Coady International Institute and has been implemented in various countries of the global South since the early 2000s (Mathie and Cunningham, 2008;

Mathie et al., 2009, 2017; Ghore, 2015). With the help of various ABCD tools, communities define their own development priorities in view of existing assets, strengths, and related opportunities. In line with these community-defined priorities, the project supported targeted agricultural and agroforestry practices that are based on and responsive to the relevant communities’ identities (who they are), interests (their rational calculations), and preferences (what they like) (Fuchs et al., 2019a,b). By supporting community-selected and community-driven activities, the project pursued various overarching aims, including rehabilitation of degraded land in the basin through the sustainable inclusion of trees and shrubs on farm to improve environmental services, alongside increased food security and improved livelihoods. The project worked with four community groups, two in lower Nyando and two in middle Nyando, with a total membership of 116 from 98 households (see Table 1).

The lower Nyando site is in Kisumu County at latitude 0° 7' N, longitude 34° 24' E, with an elevation range of 1,000–1,300 m above sea level. The middle Nyando site is in Kericho County at latitude 0° 24' S, longitude 35° 43' E, with an elevation range of 1,300–1,800 m above sea level. The climate in the Nyando River basin varies from humid to sub-humid. Rainfall in both lower and middle Nyando is bimodal; long rains occur between March and May, while short rains occur between October and November. Mean annual rainfall in lower Nyando and middle Nyando ranges between 800 and 1,200 mm and 1,200–1,600 mm, respectively. The mean annual minimum and the maximum temperature ranges between 12 and 16°C and 29–31°C in lower Nyando and 9–14°C and 27–31°C in middle Nyando. Dominant soil types are luvisols and gleysols in lower Nyando and leptosols and cambisols in middle Nyando (Verchot et al., 2008).

Agriculture is the main land use activity in the region and a vast majority of the population in the basin depend on agriculture for their livelihood (Boye et al., 2008). The mean farm size is two acres in lower Nyando and three acres in middle Nyando (Fuchs and Neufeldt, 2014). Agricultural activities in the area include livestock keeping and subsistence crops farming of maize, beans, sorghum, and millet, while coffee and sugarcane are the main commercial crops. The Nyando River basin is one of the most degraded of all the river basins in the Kenyan portion of Lake Victoria alongside Yala River and Nzoia River basins (World Bank, 2010). Besides food crops, shrubs and grasses make up the dominant vegetation. Livestock grazing and charcoal burning have been cited as the leading cause of low vegetation diversity in the area (World Bank, 2010).

Field Measurements

Inventory measurements were conducted on farms of households that were previously selected for ICRAF’s ABCD climate change adaptation and mitigation pilot project. The surveyed households included members of eight community groups, evenly distributed across the blocks. In both blocks, two of the research groups had participated in the project (project groups) and two had not (control groups). Basic characteristics, including location, dominant land use, mean land size and approximate age of group

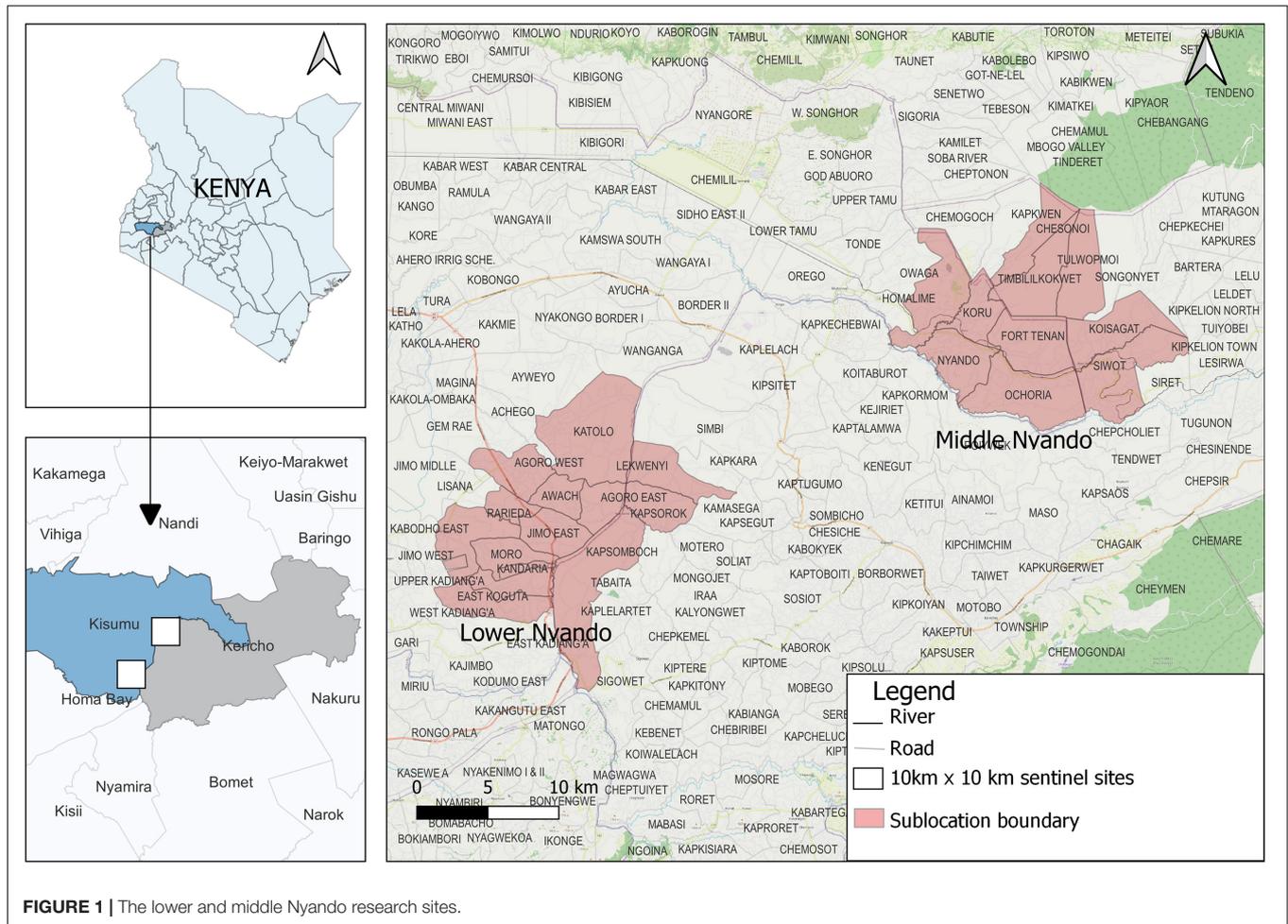


TABLE 1 | Self-Help Groups (SHG) and Women’s Group (WG) participating in the asset-based community-driven development (ABCD) pilot project in Lower and Middle Nyando in Western Kenya.

Name	Kokumu Aora Gully Rehab. SHG	Tim Kenda Kouko WG	Ochoria Greener Globe SHG	Toben Gaa SHG
Location	Lower Nyando	Lower Nyando	Middle Nyando	Middle Nyando
Administrative location†	Kisumu; Nyakach; East Nyakach; Jimo East	Kisumu; Nyakach; North-East Agoro; Awach	Kisumu; Muhoroni; Fort Ternan; Ochoria	Kericho; Kipkelion West; Siwot; Siwot
ICRAF exposure	WKIEMP* project group; since 2006	ABCD project group; since 2010	Comart I** project group; since 2008	ABCD project group; since 2010
ICRAF exposure 2010 research (Thorlakson and Neufeldt, 2012)	Four years in project	Control group	Two years in project	Control group
ICRAF exposure 2014 research	Eight years in project	Four years in project	Six years in project	Four years in project
Number of members	32	20	20	44
Number of households	26	20	20	32

†Administrative localization indicated in County; Sub-County; Location; Sub-Location.

*The Western Kenya Integrated Ecosystem Project implemented by KARI and ICRAF from 2005.

**The Comart I project was a food-for-work project funded by the same donor, before adopting an ABCD approach.

members, were kept constant between each project group and its control group. Altogether, the research groups had 256 members from 189 households (see **Table 2**).

Given the difference in household numbers in each research group, and due to limited funding and time to carry out the research, 14 households were selected from each of the eight

TABLE 2 | Overview of community groups, households and land size included in the research.

Research group name and acronym	Sub-sample name and acronym	Total members	Total households	Households sampled	Households analyzed	Land owned by analyzed households (ha)
Kokumu Aora Gully Rehabilitation SHG (LP1) Tim Kenda Kouko WG (LP2)	Total lower project (TLP)	52	46	28	23	18.41
Nen Mos SHG (LC1) Kobiero Moyie WG (LC2)	Total lower control (TLC)	66	49	28	28	15.99
Ochoria Greener Globe SHG (MP1) Toben Gaa SHG (MP2)	Total middle project (TMP)	64	52	28	27	33.61
Wang' Buono Tree Nursery SHG (MC1) COSMAZ Round SHG (MC2)	Total middle control (TMC)	74	42	28	28	26.10
Total		256	189	112	106	94.11

SHG, self-help group; WG, women group; LP, lower project; LC, lower control; MP, middle project; MC, middle control.

groups by applying a stratified random sampling method. The sub-sample size was considered sufficient to capture the variation in spatial land size, tree/shrub species and their biomass across the study area. Hence, a total of 112 households were interviewed and their farms surveyed between May and September 2016.

Agroforestry practices found on individual farms of the surveyed households were classified according to the predominant arrangement and management of the trees/shrubs that were present, in line with terminology used in Nair (1993). Tree/shrub arrangements assessed were classified in five different practices: hedgerows, multipurpose trees on farm (MPTs), riparian buffers, woodlots, and boundary planting. To assess biomass of individual trees/shrubs, diameters at breast height (DBH) measurements were taken from each tree/shrub at 1.3 m above the ground level, using a regular tape measure held horizontally and tightly over bark. In case of bifurcations, forks, or swollen sections at the 1.3 m mark, appropriate protocols for measurement were followed. The DBH of the separate stems was calculated as the square root of the sum of squares of individual stems (West, 2009). The scientific name of the tree/shrub was recorded where known; and the local or English name of the species was recorded where the scientific name could not be identified in the field. The area (hectare, ha) under agroforestry practice was determined by using a Geographic Positioning System (GPS, Trimble JUNO 3D). The stretch of land under boundary planting was recorded as length in meters.

Data Analysis

The tree data were grouped into five DBH classes of [< 10 , $10-20$, $20-30$, $30-40$, and > 40 cm] to present frequency and biomass estimates of trees/shrubs in different diameter classes. The five classes were enough to achieve adequate spread of diameter classes of the sample. Shannon-Weiner diversity index (H) was used to describe the alpha diversity in each agroforestry practice. Different species were counted, and diversity index and other statistical analyses were calculated based on counts and proportion of individuals using Microsoft Excel and R (R Core Team, 2016).

Species specific allometric equations by Tumwebaze et al. (2013) were used to estimate the biomass of *Markhamia*

lutea ($AGB = 0.07502 \times DBH^{2.42}$) and *Grevillea robusta* ($AGB = 0.01 \times DBH^{1.81}$). The equation by Kuyah et al. (2013) for eucalyptus ($AGB = 0.085 \times DBH^{2.471}$) was applied to trees of this genera. Biomass for the rest of the species was determined using the generic equation for trees in agricultural landscapes in western Kenya ($AGB = 0.091 \times DBH^{2.472}$) (Kuyah et al., 2012a). The sum of biomass estimates of individual trees/shrubs in different agroforestry practices was divided by respective land area to obtain biomass in $Mg\ ha^{-1}$. Biomass for trees in boundary planting was converted to $Mg\ ha^{-1}$ by calculating the area occupied by boundary trees and assuming a width of 2 meters (Reppin et al., 2019).

Data from a total of 106 households were considered in the analysis after removing six households whose values were considerably different from other observations in the dataset (see **Table 2**). Quantitative biophysical data was triangulated with qualitative interview data. Data presentation in the results section follows the following sequence in most sub-sections: (a) results from the entire dataset, (b) regionally differentiated results, and (c) comparison of results between project and control groups that are aggregated at landscape level, and hence separately for both regions. Considering the importance of the biophysical context on land use and management in the region, and the interest in highlighting project effects, comparing the four "group-in-site" sub-samples, namely (total) lower project, (total) lower control, (total) middle project, and (total) middle control, is fundamental. In some instances, comparisons of individual research groups and their control groups are added.

RESULTS

Descriptive Statistics

The descriptive analyses of the dataset are shown in **Table 3**. The size of the land owned, and land operated was significantly higher in the middle region than in the lower region samples. Furthermore, the number of male-headed households was significantly higher in middle, while the age of the head of household was significantly higher in lower Nyando (**Table 3**). In the lower Nyando sample, there were no significant differences

TABLE 3 | Summary of household socioeconomic characteristics.

Characteristic	TLP	TLC	TMP	TMC	Lower	Middle	Overall
Household size	6.2 ^a	6.3 ^a	6.3 ^b	5.0 ^b	6.2 ^c	5.7 ^c	5.9
Land owned (ha)	0.80 ^a	0.57 ^a	1.24 ^b	0.93 ^b	0.67 ^c	1.09 ^{s***}	0.89
Land operated (ha)	0.47 ^a	0.41 ^a	1.02 ^{s**}	0.69 ^b	0.43 ^c	0.85 ^{s***}	0.65
Age of household head (years)	59 ^a	56 ^a	46 ^b	50 ^b	57 ^{s***}	48 ^c	52
Household head is male (%)	69.6 ^a	50.0 ^a	92.6 ^b	78.6 ^b	58.8 ^c	85.5 ^{s***}	72.6
Number of households	23	28	27	28	51	55	106

Sub-samples include: TLP, total lower project; TLC, total lower control; TMP, total middle project; TMC, total middle control. Superscript "a" is for comparison between TLP and TLC. Superscript "b" is for comparison between TMP and TMC. Superscript "c" is for comparison between Lower and Middle. If comparison is superscript "s," the difference is significant at **($P < 0.05$) or ***($P < 0.01$) for a Welch one-way test.

TABLE 4 | Distribution of tree/shrub sizes across sub-samples and regions.

Groups	Proportions by DBH (%)					Totals
	DBH < 10 cm	10–20 cm	20–30 cm	30–40 cm	DBH > 40 cm	
TLP	80%	17%	3%	0%	0%	100%
TLC	62%	31%	4%	2%	1%	100%
Total lower	69%	26%	4%	1%	0%	100%
TMP	50%	37%	9%	3%	1%	100%
TMC	39%	39%	14%	5%	3%	100%
Total middle	47%	38%	11%	3%	1%	100%
Overall total	54%	34%	8%	3%	1%	100%

Sub-samples include: TLP, total lower project; TLC, total lower control; TMP, total middle project; TMC, total middle control. Tree diameter sizes were grouped into 5 DBH classes in intervals of 10 cm. Results are indicated in total numbers (n) and respective percentages for individual samples, aggregated samples per region, as well as at regional level and for the entire dataset. Percentages are attributed along the rows.

between project and control groups in any characteristic. In the middle Nyando sample, the size of land operated was higher in the project than in the control groups.

Tree and Shrub Species Number and Size Distribution

A total of 9,699 trees/shrubs were inventoried, 3,353 (35%) on farms surveyed in lower Nyando and 6,346 (65%) on middle Nyando farms (Table 4). Overall, the total number of trees, the species diversity, and biomass were significantly higher on farms assessed in middle Nyando than in lower Nyando. One-way ANOVA test (with no assumption of equal variances) was used to assess differences in mean tree density (per hectare) between regions, then between aggregated project and control groups within the regions (Table 5).

Altogether, tree densities for DBH < 10 cm and DBH (30–40 cm) were the highest and lowest, respectively. For trees of DBH > 10 cm, mean tree density was significantly different ($P < 0.05$) between lower and middle Nyando regions. Households in the middle Nyando region reported significantly

TABLE 5 | Vegetation structure (tree density per ha) comparing differences across sub-samples and regions (using one-way ANOVA).

DBH class (cm)	TLP	TLC	TMP	TMC	Lower	Middle	Total density (sd)
<10	71.22 ^a	79.6 ^a	100.7 ^b	53.8 ^b	75.8 ^c	76.8 ^c	76.3 (76.2)
10–20	17.3 ^a	43.4 ^{s**}	75.5 ^{s**}	42.7 ^b	31.7 ^c	58.4 ^{s***}	45.7 (52.2)
20–30	3.6 ^a	9.8 ^{s**}	16.9 ^b	17.5 ^b	7.4 ^c	17.2 ^{s***}	13.1 (16.1)
30–40	0.6 ^a	4.6 ^{s**}	5.6 ^b	5.0 ^b	4.2 ^c	5.3 ^c	4.9 (5.3)
>40	0.4 ^a	2.1 ^a	2.6 ^b	3.3 ^b	1.8 ^c	2.9 ^c	2.7 (2.4)
Overall	90.0 ^a	132.5 ^{s**}	198.0 ^{s*}	114.6 ^b	113.4 ^c	154.7 ^{s*}	134.6 (126.7)

Sub-samples include: TLP, total lower project; TLC, total lower control; TMP, total middle project; TMC, total middle control. Tree diameter sizes were grouped into 5 DBH classes in intervals of 10 cm. Superscript "a" is for comparison between TLP and TLC. Superscript "b" is for comparison between TMP and TMC. Superscript "c" is for comparison between Lower and Middle. If comparison is superscript "s," the difference is significant at *($P < 0.1$) or **($P < 0.05$) or ***($P < 0.01$) for a Welch one-way test. The tree density is the number of trees per hectare. Values for diameter at breast height (DBH) and tree density represent mean and standard deviation (SD).

greater tree densities than the lower Nyando region for trees of DBH > 10 cm. Mean tree densities for some DBH classes differed significantly between lower project and lower control groups and also between middle project and middle control groups. Overall, lower project had the highest tree/shrub densities per hectare compared to lower control, middle project, and middle control (Table 5). However, we acknowledge that the smaller size of land in middle project groups (Table 4) and proportion of trees (Figure 2), likely contributed to the very high tree density, especially for the younger trees of DBH < 20 cm. It is noteworthy that the percentages of smaller diameter trees/shrubs (DBH < 10 cm) were higher among all project groups than among their respective control groups (Table 4); indicating that a higher proportion of the tree population found on the farms of project group members were younger in age and had been planted or maintained within the previous years.

Looking at the data at a landscape level (Table 4), and hence aggregating the data from the project groups and the control groups in each region, the lower control groups had 1.6 times more trees/shrubs than the lower project groups (Table 4). Conversely, the middle project sample had 2.4 times higher numbers of trees/shrubs on farm than the middle control sample (Table 4). While project and control groups in lower Nyando had almost equal numbers in small diameter trees (DBH < 10 cm), these represented a considerably higher percentage for the lower project (79%) than the lower control groups (62%) (Figure 2). Intermediary diameter trees/shrubs (10–40 cm) were almost three times as many in absolute terms in lower control than in lower project, representing 37% in the lower control and 20% in the lower project samples. Large diameter trees/shrubs (DBH < 40 cm) were scarce in both lower project and lower control (Table 4). In middle Nyando, the middle project sample had more than twice as many trees overall, more than three times as many in the small diameter class, and almost twice as many in the medium diameter class. Similar to lower Nyando, this translated to higher percentages of trees on farm being small diameter trees in the middle project sample (50%) than in the

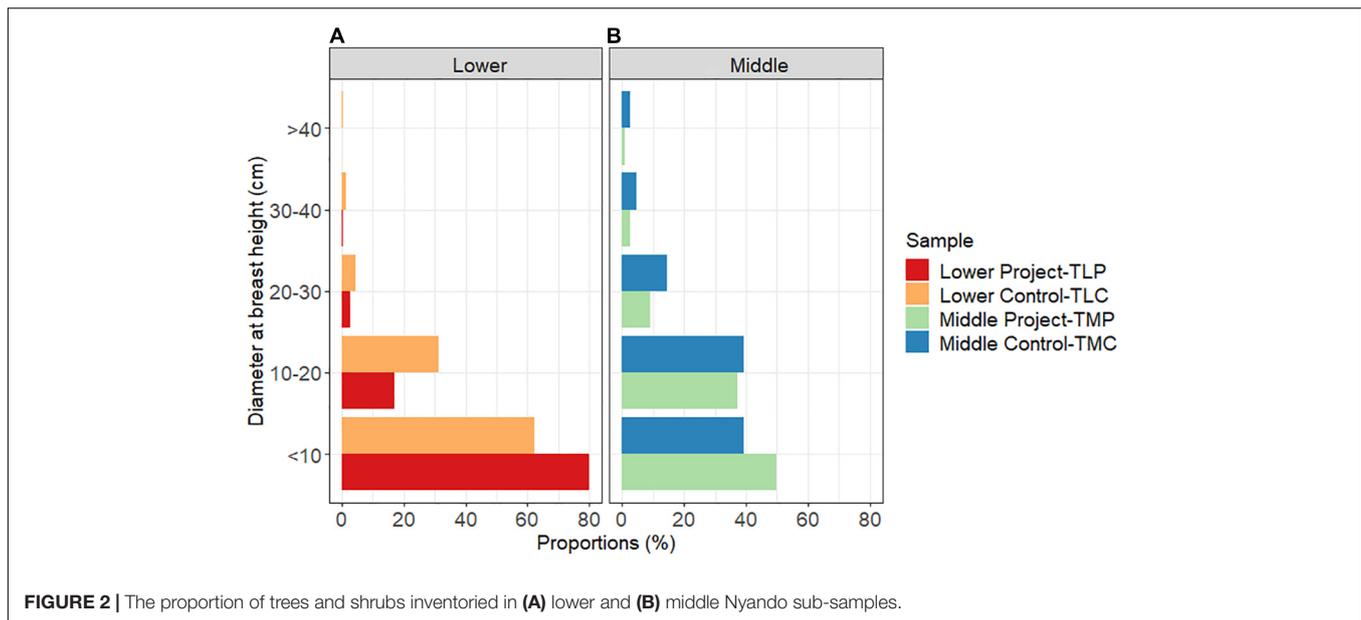


FIGURE 2 | The proportion of trees and shrubs inventoried in (A) lower and (B) middle Nyando sub-samples.

middle control sample (39%), reiterating the fact that more trees were planted among project groups than among control groups in previous years. While overall few in numbers, large diameter trees/shrubs (DBH > 40 cm) were fewer (1%) in the middle project than in the middle control samples (3%).

Tree and Shrub Species Diversity in Different Agroforestry Practices

The total of 9,699 trees and shrubs inventoried belonged to 102 species and were found throughout an area of 11.104 hectares and 12,198.102 m. This area had 106 households and the trees were distributed over five agroforestry practices across the lower and middle Nyando regions. Overall, according to the Shannon-Weiner index, the diversity of the entire sample was $3.08 (\pm 0.01)$. The diversity index in middle Nyando was $2.83 (\pm 0.01)$, and hence slightly higher than $2.74 (\pm 0.01)$ in lower Nyando (see Table 6).

In the lower block, 48 species were identified, nine of which were indigenous and 39 were exotic tree species. Of the 48 species, 37 were tree and 11 were shrub species. Furthermore, 1,261 saplings, trees/shrubs of DBH < 2.5 cm of various species, were counted in the region. The most common exotic trees were *Grevillea robusta* and *Euphorbia tirucalli* and indigenous trees were *Balanites aegyptiaca* and *Markhamia lutea* in lower Nyando. The total lower project sample had a higher species diversity than lower control sample at $2.94 (\pm 0.01)$ and $2.30 (\pm 0.02)$, respectively. These trees were also utilized in more diverse agroforestry practices in the lower project than in the lower control samples. Trees/shrubs were found in five different agroforestry practices in lower project sample, compared to three practices in lower control groups. The most popular arrangement of these trees, and hence the most common agroforestry practice, was boundary planting in both total project and control samples in lower Nyando. Overall, in

lower Nyando, 43 and 79% of trees/shrubs were inventoried in boundary planting arrangements in lower project and lower control samples, respectively. Tree and shrubs species' diversity varied across the different agroforestry practices identified in lower project and lower control. Multipurpose trees on farmland had the highest diversity index, $2.82 (\pm 0.01)$ and $2.78 (\pm 0.02)$, in lower project and lower control samples, respectively.

In middle Nyando, 39 indigenous and 56 exotic species, and hence a total of 95 tree/shrub species were inventoried; of which 67 were tree and 28 were shrub species. Furthermore, 5,468 saplings of various species were counted in the region. The most common exotic trees were *Grevillea robusta*, *Cupressus lusitanica*, while the most common indigenous trees were *Spathodea campanulata* and *Markhamia lutea*. The middle project sample had a lower species diversity than the middle project sample, with a Shannon-Weiner diversity-index [H] of $2.55 (\pm 0.00)$ and $3.09 (\pm 0.01)$, respectively. The middle project and middle control samples both had four different agroforestry practices each. Boundary planting had the highest number of trees/shrubs in the middle project sample (38%), while most trees/shrubs in the middle project sample were found in multipurpose trees on farmland (MPTs) arrangements (53%). In both the middle project and the middle control samples, MPTs was the agroforestry practice with the highest tree and shrub species diversity at $3.17 (\pm 0.01)$ and $3.21 (\pm 0.01)$, respectively.

Interestingly, hedgerows were only planted by project groups in both regions, while riparian buffers were only found in the lower project and middle control samples. The three other practices were recorded in all four sub-samples.

Trees and Shrubs Biomass Estimates and Carbon Stocks

Across the entire sample, present mean AGB per farm was estimated at 8.33 Mgha^{-1} . Concerning the regional differences,

TABLE 6 | Species diversity in various agroforestry practices across sub-samples and regions.

Sample	Agroforestry practices	% of Total trees and shrubs	Total area recorded	Shannon-Weiner diversity index [H]	[H] group type per region	[H] per region	[H] altogether
TLP	Hedgerows	14%	0.173 ha	1.91 (\pm 0.04)	2.94 (\pm 0.01)	2.74 (\pm 0.01)	3.08 (\pm 0.01)
	MPTs	27%	0.568 ha	2.86 (\pm 0.01)			
	Riparian buffers	4%	0.183 ha	1.51 (\pm 0.09)			
	Woodlots	13%	0.335 ha	2.64 (\pm 0.11)			
	Boundary planting	43%	0.257 ha	2.58 (\pm 0.03)			
TLC	MPTs	21%	1.219 ha	2.78 (\pm 0.02)	2.30 (\pm 0.02)		
	Woodlots	<0.001%	0.057 ha	0.67 (\pm 0.03)			
	Boundary planting	79%	0.575 ha	2.02 (\pm 0.02)			
TMP	Hedgerows	20%	2.008 ha	1.32 (\pm 0.01)	2.55 (\pm 0.00)	2.83 (\pm 0.01)	
	MPTs	25%	3.322 ha	3.17 (\pm 0.01)			
	Woodlots	17%	0.534 ha	2.17 (\pm 0.02)			
	Boundary planting	38%	0.868 ha	2.27 (\pm 0.01)			
TMC	MPTs	53%	2.617 ha	3.21 (\pm 0.01)	3.09 (\pm 0.01)		
	Riparian buffers	1%	<0.001 ha	0.49 (\pm 0.07)			
	Woodlots	6%	0.087 ha	2.15 (\pm 0.02)			
	Boundary planting	39%	0.723 ha	2.66 (\pm 0.01)			

Sub-samples include: TLP, total lower project; TLC, total lower control; TMP, total middle project; TMC, total middle control. Area under boundary planting converted to hectares by assuming a width of 2 m. Shannon-Weiner diversity index [H] presented as (mean \pm SE); SE is standard error.

TABLE 7 | Trees and shrubs biomass estimates across sub-samples and regions.

Sample	TLP	TLC	TMP	TMC	Lower	Middle	Overall
Households	23 ^a	28 ^a	27 ^b	28 ^b	51 ^c	55 ^c	106
Total AGB (Mgha ⁻¹)	35.02 ^a	106.24 ^{s***}	457.44 ^{s***}	284.52 ^b	141.26 ^c	741.96 ^{s***}	883.22
Total AGB per farm (Mgha ⁻¹)	1.52 ^a	3.79 ^{s***}	16.94 ^{s***}	10.16 ^b	2.77 ^c	13.49 ^{s***}	8.33

Sub-samples include: TLC, total lower control; TMP, total middle project; TMC, total middle control. Superscript "a" is for comparison between TLP and TLC. Superscript "b" is for comparison between TMP and TMC. Superscript "c" is for comparison between Lower and Middle. If comparison is superscript "s," the difference is significant at ***($P < 0.01$) for a Welch one-way test. Mean comparisons done first between groups in region, then between regions.

the total estimated mean AGB per farm of the 55 farms assessed in middle Nyando was 13.49 Mgha⁻¹ and hence significantly higher ($P < 0.001$) than the 2.77 Mgha⁻¹ assessed on the 51 farms in lower Nyando (Table 7). Farms in lower project groups had significantly lower biomass estimates than farms in lower control groups. On the other hand, farms in middle project groups had significantly higher biomass estimates than those in middle control groups.

Biomass Contributors by Diameters at Breast Height Class

Overall, trees with DBH of 10–20 cm (39.2%), and DBH less than 10 cm (23.7%) contributed the most AGB in the whole sample. In middle Nyando, 78.7% of AGB was contributed by trees that had a DBH of less than 30 cm. In lower Nyando, the majority of AGB (86.2%) was also from trees with DBH that was less than 30 cm. However, middle Nyando had more AGB (11%) from large high biomass trees (DBH > 40 cm) compared to only 5.7% in lower Nyando. Trees with DBH of less than 30 cm contributed the most AGB (89%) in the lower Nyando project sample (TLP). Similarly, most of the biomass in the lower Nyando control sample (TLC) was found in intermediary diameter trees (10–30 cm). Consequently, they contributed most of the AGB

(see Figure 3). Trees with DBH of less than 20 cm contributed over half of the AGB in the middle project and middle control samples. High biomass trees (DBH > 40 cm) stocked a small fraction of the estimated AGB in lower Nyando; 7 and 5% in the lower project and in the lower control samples, respectively. At the same time, higher intermediary diameter trees (DBH = 30–40 cm) held a considerable proportion (11%) of AGB in the lower control sample, unlike in the lower project sample (3%). Conversely, they stocked a significant proportion of biomass in middle Nyando; 11% in the middle project and 10% in the middle control samples, respectively. All results are included in Figure 3.

Biomass Estimates Per Agroforestry Practice

Considering one of the core contributions of this paper, biomass stock potentials of different tree and shrub arrangements, the assessment of AGB of various agroforestry practices provided interesting insights. Woodlots contributed most AGB per farm with 7.92 Mg/ha, boundary planting contributed 4.91 Mg/ha, hedgerows had 5.22 Mg/ha, and MPTs contributed 1.76 Mg/ha. Riparian buffers contributed the highest AGB per farm at

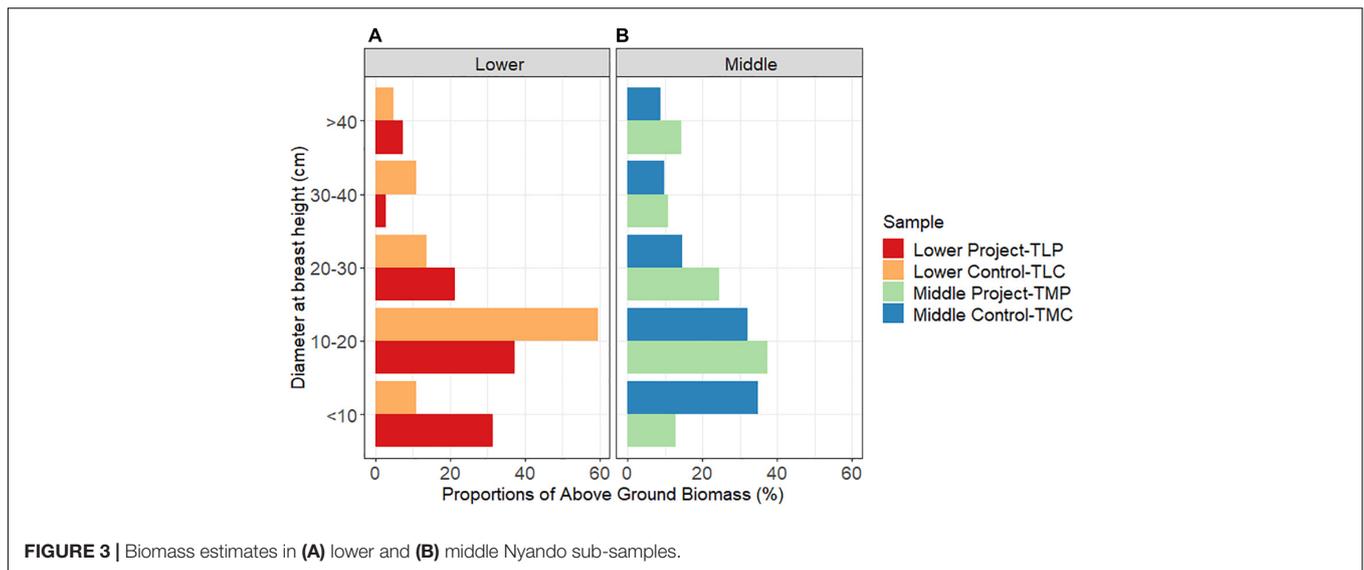


TABLE 8 | Estimated AGB per agroforestry practice across sub-samples.

Sample	Agroforestry practices	% of Total trees and shrubs	Total area (hectares)	Number of households	Mean DBH (cm)	Above-ground biomass [AGB] per farm (Mg/ha)
TLP	Boundary planting	42.5	0.257	17	7.6 (4.9)	3.45
	Hedgerows	14.1	0.173	4	5.3 (2.7)	3.76
	MPTs	26.9	0.568	20	7.8 (5.7)	1.04
	Riparian buffers	3.7	0.183	1	6.8 (4.4)	5.19
	Woodlot	12.8	0.335	6	7.7 (5.4)	2.31
TLC	Boundary planting	79.1	0.610	28	9.7 (5.8)	4.34
	MPTs	20.6	1.219	25	11.1 (8.1)	1.05
	Woodlot	0.2	0.057	1	5.2 (1.5)	0.52
TMP	Boundary planting	37.6	0.868	23	11.3 (7.2)	7.28
	Hedgerows	20.0	2.008	9	12.4 (8.1)	5.87
	MPTs	25.3	3.322	27	14.5 (10.2)	1.85
	Woodlot	17.0	0.534	14	9.6 (6.0)	5.31
TMC	Boundary planting	39.4	0.741	24	13.4 (8.1)	4.34
	MPTs	53.4	2.617	26	16.1 (11.8)	2.92
	Riparian buffers	1.1	<0.0001	1	6.6 (2.7)	223.87
	Woodlot	6.1	0.087	3	11.9 (6.0)	33.75

Sub-samples include: TLP, total lower project; TLC, total lower control; TMP, total middle project; TMC, total middle control.

114.53 Mg/ha but was excluded¹ from further analysis because it included data from only two households. In lower Nyando, riparian buffers contributed most AGB per farm, followed by boundary planting and hedgerows (Table 8). In middle Nyando, riparian buffers contributed the most AGB per farm, followed by woodlots, hedgerows, and boundary planting (Table 8).

In the lower project sample, riparian buffers contributed the most biomass, followed by hedgerows (Table 8). In lower control, boundary planting contributed the most biomass, which was also the practice that contributed the most biomass in the middle project groups (Table 8). Riparian buffers and woodlots

contributed the first and second most biomass in the middle control sample, respectively. However, this can be attributed to the small sample sizes, which makes the contribution by boundary planting at 4.34 Mg/ha also considerable.

Dominant Biomass Contributor Species

Certain individual tree and shrub species, both indigenous and exotic, contributed over-proportionally to total biomass estimates across the two regions. Overall, *Grevillea robusta* contributed 34.1% of total biomass, *Eucalyptus* sp. contributed 4.8%, while *Ficus sur* contributed 4.6%. In lower Nyando, *Eurphobia tirucalli* contributed 16.5% of total biomass, *Balanites aegyptiaca* contributed 15.1% while *Grevillea robusta* contributed 14.4% of biomass within the site. In middle Nyando, *Grevillea robusta* was the highest dominant biomass contributor with

¹The mean AGB/ha under riparian buffers was very high. This was first attributed to the species (eucalyptus) and that they grow next to a river. Furthermore, the relative area with the trees is small leading to a high AGB/ha.

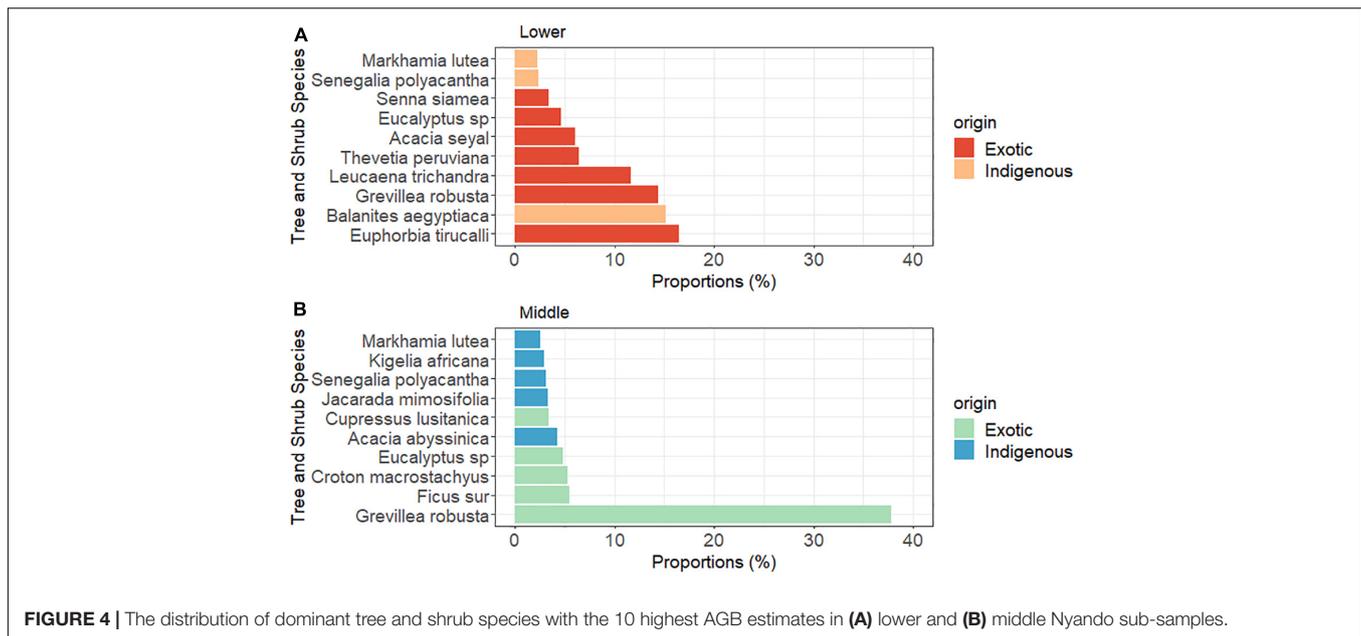


FIGURE 4 | The distribution of dominant tree and shrub species with the 10 highest AGB estimates in (A) lower and (B) middle Nyando sub-samples.

37.8% of sample total, *Ficus sur* contributed 5.4% while *Croton macrostachyus* contributed 5.3% of total site biomass. Among those species that contributed AGB > 0.2 Mg, which represents the minimum threshold set for relative dominance in this study, the top three in each group type are considered (see **Figure 4**).

Dominant trees in the lower project sample were *Balanites aegyptiaca*, *Grevillea robusta*, and *Thevetia peruviana*, which held 27.8, 12.1, and 11.9% of the total biomass respectively, while *Euphorbia tirucalli*, *Grevillea robusta*, and *Leucaena trichandra* held 20.3, 15.1, and 14.7% of the total biomass in the lower control sample (see upper section of **Figure 4**). In middle Nyando, *Grevillea robusta*, *Eucalyptus sp.*, and *Ficus sur* held 50.9, 4.7, and 4.1% in the middle project sample, while *Grevillea robusta*, *Croton macrostachyus*, and *Ficus sur* held 16.9, 11.3, and 7.5%, respectively, in the middle control sample (see lower section of **Figure 4**). Overall, the top three dominant biomass contributors were exotic species. All three dominant contributors in middle Nyando were exotic species, while two out of three dominant species in lower Nyando were exotic. In all group-in-site samples (lower project, lower control, middle project, and middle control), at least two out of the top three dominant tree species in the other samples were of exotic origin.

DISCUSSION

Understanding the Extent and Drivers of Differences in Tree Numbers, Species Diversity and Overall Above-Ground Biomass

Overall, the number of inventoried trees and shrubs was much higher, and there were considerably higher numbers of large diameter trees, in middle Nyando than in lower Nyando. Conversely, the landscape in lower Nyando was dominated

by low-biomass trees/shrubs, which contributed to lower AGB within the site. Large trees were few, most likely because of considerable harvesting for fuel wood, timber and charcoal burning in the past, as indicated in *Boye (2002)*. The dominance of low and intermediary-biomass trees also points toward farmers having integrated new trees/shrubs in their farms and/or allowed for natural regeneration. In that vein, many interviewed households across all four project groups suggested that their engagement in agroforestry was driven by an interest in socio-ecological services provided by trees on farm that had been promoted in project trainings. While the tree density was higher due to the smaller size of farms owned among lower project than lower control sample households, the former had considerably fewer trees/shrubs on farm than the latter despite having obtained tree/shrubs seedlings through the project. Qualitative data showed that the Lower Project 2 research group was essentially composed of elderly widowed women, which had contributed to low engagement in agroforestry and hence to low tree numbers, species diversity and overall AGB. Interview data revealed other barriers to engagement in agroforestry in lower Nyando, including frequent dry spells, and an absence of reliable water sources, which had led to the drying up of the seedlings in the community tree nursery. Furthermore, control group members had seemingly adopted practices that were promoted to project groups by virtue of being neighbors and relatives. The project hence had a spill-over effect and contributed to the adoption of agroforestry among the control group members, similar to observation made in *Noordin et al. (2001)*.

On the other hand, the middle project sample had considerably higher number of trees and shrubs than the middle control sample. A larger proportion of the trees/shrubs in the middle project were small diameter trees than in the control sample, while the proportion of larger diameter trees/shrubs was higher in the middle control sample. According to the qualitative

data, middle project households planted many seedlings and prioritized seedling survival. The high seedling survival rate was partly related to ICRAF trainings that emphasized the value of conserving and planting more trees/shrubs on farm. Middle Project 1 members reported having collectively decided to eliminate all goats from their households, which had previously browsed on young trees/shrubs and had hence inhibited seedling survival, as observed in Alain and Serigne (2007). The implementation of seedling survival-enhancing techniques was also evident from the high number of saplings recorded in the middle project sample. Similarly, large-biomass trees, which were remnants of the natural degraded forest and had been preserved through FMNR, were frequent among both project and control groups in this region. Further, the high proportion of AGB stemming from large diameter trees in Middle Control 2 research group was related to the presence and protection of a few, but very large indigenous trees, among which *Kigelia africana*, *Ficus sur*, and *Jacaranda mimosifolia*, whose DBH were between 60.5 and 102.5 cm.

Diversity in Agroforestry Practices, Species Diversity, and Impact on Above-Ground Biomass

Boundary planting was the most common agroforestry practice in both regions, and most trees/shrubs recorded were inventoried in this arrangement. This popularity might be attributed to the fact that farmers used trees/shrubs to fortify their farm boundaries, either between farms or between sections within the same farm, in line with the findings of Nyaga et al. (2015). However, boundary planting, overall, had low diversity, which might be attributed to the farmers' preference for *Grevillea robusta* and *Leucaena* species for fuel wood, fodder, timber, and shading. However, *Grevillea robusta* was the largest single contributor of AGB in the study sample. Among the five inventoried practices, riparian buffer planting was the least common, since only a few farmers' farms were bordering a river. Considering the small sample and the small area under the practice, AGB from riparian buffers was considerable. The highest tree/shrub species diversity was recorded in MPTs, which can be attributed to the various purposes that these diverse trees have, including provision of fruits, use of leaves as vegetables, fertilizer and their shade and aesthetic value. Woodlots also had high diversity in all the samples, except in the lower control sample, where only one farmer had planted a woodlot. Overall, high diversity in woodlots can be attributed to the fact that woodlots are primarily planted for fuel wood, in line with findings of Akinnifesi et al. (2008), and that farmers typically opt for different fast-growing trees/shrubs to diversify the source of this valuable commodity (Iiyama et al., 2014; Yonemitsu et al., 2014). Hedgerows were exclusively found in the project samples in both regions and were mostly planted with *Grevillea robusta*. Low diversity and high frequency of *Grevillea robusta* in hedgerows can be equated with hedgerows being primarily used for shade in coffee sections on-farm, specifically in Middle Project 1, while in they were used to shade food crops in Lower Project 1.

Overall, engagement in agroforestry contributed to improved biodiversity on agricultural lands, which agrees with the findings

of Scherr (1995) and McNeely and Schroth (2006). Farmers in both regions had more exotic trees/shrubs than indigenous trees, which can be attributed to fuel wood, fodder and fertilizer being sourced from fast-growing exotic trees/shrub species like *Grevillea robusta* and *Leucaena* species. This was also reported in terms of farmer preference for particular trees/shrubs that match their interests (Nyaga et al., 2015). The species diversity in the lower project sample was higher than in the lower control sample, and lower in the middle project than in the middle control sample, despite the significantly higher number of trees/shrubs found in the middle project sample.

Overall Biomass Estimates, Biomass Per Tree/Shrub Size, and Dominant Contributor Species

In the total lower project sample, a total of 805 "project" trees/shrubs, which farmers indicated having planted during or after the project, contained about 2.27 Mgha⁻¹ of AGB per farm, while holding 479 trees/shrubs containing 2.65 Mgha⁻¹ that farmers had planted out of their own initiative before the project or that had been found on the land previously. Similarly, 3,245 "project" trees/shrubs containing 6.74 Mgha⁻¹ of the total biomass estimates per farm in the middle project sample were inventoried, compared to 1,209 containing 6.03 Mgha⁻¹, which farmers had planted previously or found on their land. These results illustrate that conservation of large old diameter trees is important because they only represented 1% of the total number of trees/shrubs inventoried, but contained 22% of the AGB. Since the numbers of trees planted during or after the project were by far higher than pre-existing trees in both regions, future AGB increases in both areas is likely. In the lower project sample, AGB was directly proportional to the number of agroforestry practices and the numbers of trees/shrubs inventoried, while the AGB was proportional to the number of trees/shrubs inventoried in the lower control sample. In the middle project and middle control samples, biomass results were mainly influenced by a large number of moderate size trees/shrubs, their diversity and the presence of large diameter trees, similar to the observation of Kuyah et al. (2014) in Malawi.

Overall, species diversity, number of trees/shrubs, large trees/shrubs and biomass were significantly higher in middle Nyando than in lower Nyando. This is likely due to the high frequency of high-biomass trees/shrubs and the overall number of trees in all diameter classes, as well as the fact that farms were bigger overall and that there was more remnant primary forest in middle Nyando than in lower Nyando. Favorable climatic condition potentially contributed to more and bigger trees/shrubs in middle than in lower Nyando as well. Furthermore, adoption of seedling survival-enhancing farm management techniques was witnessed among MP1 members. These assumptions are in line with the assertions of Ordonez et al. (2014) on the role of socio-ecological factors in shaping the diversity pattern.

The most dominant tree species in terms of biomass, or the tree species which contributed most to the estimated AGB, were different in all the four sub-samples across the two regions. Altogether, the most dominant species were *Grevillea*

robusta, *Eucalyptus* sp., *Ficus sur*, *Croton macrostachyus*, *Balanites aegyptiaca*, *Acacia abyssinica*, *Jacaranda mimosifolia*, *Senegalia polyacantha*, *Euphorbia tirucalli*, and *Cupressus lusitanica*. Various explanations can be invoked for the dominance of these species. First, farmers seemed to be hesitant to cut the remaining few old indigenous *Balanites aegyptiaca*, *Ficus sur* and *Acacia abyssinica* trees. The readily available source of fuel wood from the faster growing *Grevillea robusta* that all farmers planted in their farms might have contributed to that. In addition, *Senegalia polyacantha* grew very fast in lower Nyando because farmers pollarded the trees and the remaining stems were left on the farm, and therefore stocked further carbon. Abundance of *Senna siamea* and *Leucaena trichandra* was likely related to them being planted by many farmers as a source of fodder for their livestock during the dry spells. Furthermore, the presence of *Euphorbia tirucalli* can potentially be related to its cultural value, since it is traditionally planted around the homestead belonging to members of the Luo community as an indicator that the household is headed by a man (Oloo et al., 2013). The tree furthermore provides a reliable source of fuel wood. *Thevetia peruviana*, considered as an invasive species, specifically in open areas, continued to spread very fast, and farmers used it for fuel wood and construction poles (GISD, 2010). *Eucalyptus* species, belonging to the most common fast-growing tree species, were also planted by many farmers as a source of fuel wood and timber. *Cupressus lusitanica*, another fast-growing species, is a good source of timber when it is fully mature, and farmers are likely to have allowed it to grow for a prolonged period for that reason, especially in middle Nyando. *Croton macrostachyus* grows very fast and farmers in middle Nyando integrated it in their coffee farms for shading.

CONCLUSION

A total of five agroforestry practices were documented in the lower and middle Nyando Blocks. In the total project and control samples in both region, boundary planting was the most common agroforestry practice. Conversely, MPTs on farmland had the highest species diversity across all four sub-samples. Biomass estimates were highest in woodlots on farmland where trees/shrubs contributed more AGB than other practices. This is a clear indication that agroforestry practices such as MPTs, woodlots and boundary planting, and fast-growing multipurpose trees/shrubs like *Grevillea robusta*, *Leucaena* sp., *Markhamia lutea* among other species, whose products and area of planting can allow for its prolonged growth on-farm, contribute significantly to smallholder agroforestry carbon in western Kenya. The biomass estimates, and tree/shrub species diversity established in this study provide benchmark information that can enable national and international policy makers and implementers to promote agroforestry practices, particularly MPTs and boundary planting, that constitute suitable, viable and economical technologies for adapting to and mitigating the adverse effects of climate change. This information can make an important contribution to NDC definition, as well as measurement, reporting and verification. The study

furthermore illustrates that ABCD approaches are suitable for the identification and sustainable implementation of context-specific options. It hence demonstrates the positive relation between deliberate project designs to preserve and foster community agency, the co-creation of sustainable land use options, and long-lasting environmental impact; and proposes a sustainable process contributing to SDG goal 15 on “life on land.”

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repository and accession number(s) can be found below: Orero et al. (2021).

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

LF: conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing—original draft, and writing—reviewing and editing. LO: data curation, formal analysis, methodology, software, validation, visualization, and writing—reviewing and editing. SN: conceptualization, data curation, formal analysis, investigation, methodology, and writing—original draft. SK: conceptualization, methodology, and writing—reviewing and editing. HN: funding acquisition and supervision. All authors contributed to the article and approved the submitted version.

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