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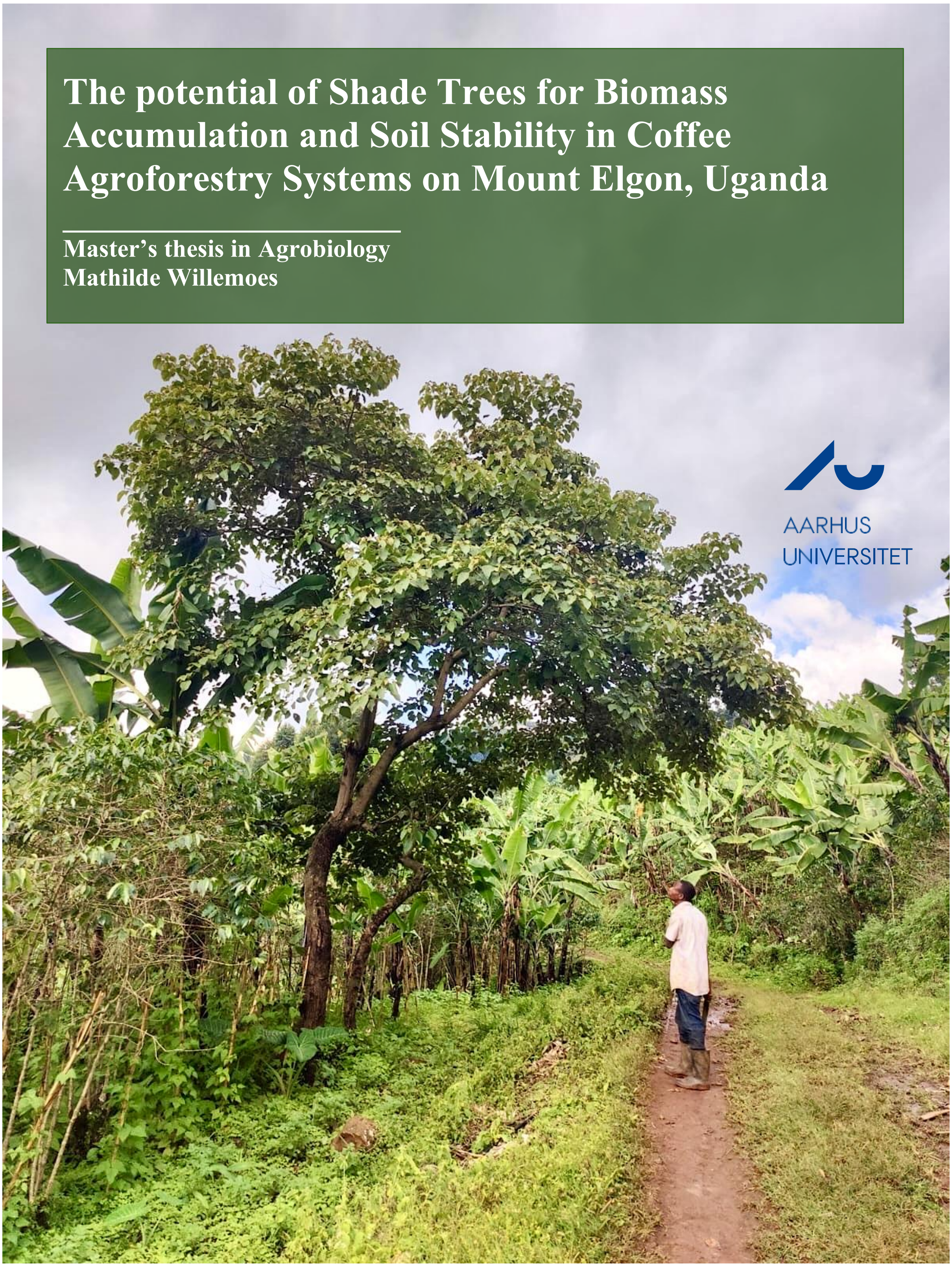
Master's thesis in Agrobiology
Mathilde Willemoes



AARHUS UNIVERSITET

Master's thesis in Agrobiology – 60 ECTS
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Table of Contents

Resumé, Dansk

Mount Elgon-regionen i det østlige Uganda har i flere årtier være præget af store miljømæssige og socioøkonomiske udfordringer. Høj befolkningstilvækst, skovrydning og intensiv arealanvendelse har medført udbredt jorderosion, forringet jordstruktur og øget risiko for jordskred. Arabica kaffe (*Coffea arabica*) er en nøgleafgrøde for småbønder i regionen, men produktionen er i stigende grad udfordret af klimaforandringer og ekstreme vejrhændelser. Skovlandbrug, hvor træer plantes sammen med kaffe i kaffeplantagerne, fremhæves som en bæredygtig løsning, der kan styrke robustheden af kaffeproduktionen overfor klimaforandringer, forbedre jordsundheden, og øge kulstoflagringen i kaffeplantagerne.

Formålet med dette studie er at undersøge potentialet af at integrere træer i småskala kaffes-kovlandbrugssystemer i tre landsbyer på Mount Elgon, med henblik på at forbedre kulstofbinding og lagring via dannelsen af overjordisk biomasse (AGB) og forbedre jordens aggregatstruktur og stabilitet. Studiet er baseret på feltmålinger af trædiversitet og densitet, højde og stammetykkelse (diameter), som danner grundlag for estimering af AGB ved hjælp af seks forskellige allometriske modeller. Derudover analyseres jordens indhold af vandstabile aggregater (WSA) som indikator for jordstabilitet, og semi-strukturerede interviews blev udført for at belyse kaffebøndernes perspektiver på erosion, træsortspræferencer og økosystemtjenester. De overordnede formål med dette studie er som følger:

1. At kortlægge densiteten og diversiteten af træer i kaffeplantager i de tre landsbyer.
2. At estimere akkumuleringen af overjordisk biomasse gennem brug af forskellige allometriske modeller.
3. At undersøge sammenhænge mellem trædække, landbrugspraksis og jordbearbejdning, og jordstruktur (WSA).
4. At analysere landmændenes perspektiver på erosion, ønskede træarter og ansete fordele og økosystemtjenester forbundet med træer i dyrkningen af kaffe.

Resultaterne afslørede lave diversitet og densitet af træer i kaffeplantagerne og en udbredt præference for eksotiske arter på bekostning af hjemmehørende arter. Dog udtrykte de fleste kaffebønder en interesse for at plante flere træer, herunder hjemmehørende arter, især på grund af skygge, jord-forbedring og muligheder for ekstra indkomst. Der blev fundet en positiv sammenhæng mellem trædensitet og jordens WSA-indhold, mens hyppig harvning og brug af frisk gødning havde en negativ effekt. De allometriske modeller viste betydelig variation i estimeringen af AGB, hvilket understreger behovet for allometriske modeller, som er tilpasset skovlandbrug og lokale dyrkningsforhold.

Studiet viser, at skovlandbrug rummer et stort, endnu uudnyttet potentiale for at styrke både robustheden af kaffedyrkningssystemer på Mount Elgon mod klimaforandringer jorderosion. For at realisere dette potentiale er det nødvendigt at tilpasse artsvalg til lokale forhold og de lokale kaffedyrkeres behov samt at fremme forvaltningspraksisser, der understøtter jordens stabilitet og kulstoflagring. Skovlandbrug kan dermed spille en nøglerolle i fremtidens bæredygtige kaffelandskaber i højlandet i det østlige Uganda.

Resumé, English

The Mount Elgon Region in Eastern Uganda has experienced serious environmental and socio-economical challenges. High population pressures, forest loss, and intensive land use have caused widespread problems with soil degradation and erosion and significantly increased the risk of landslides in the area. Arabica coffee (*Coffea arabica*) is a key crop for smallholder farmers in the region, but its production is increasingly challenged by climate change and variability and extreme weather events. Agroforestry, which integrates trees with coffee cultivation, is promoted as a sustainable solution that can increase the resilience of the coffee productions against climate change and variability, improve soil health and stability, and increase the carbon storage in the coffee gardens.

The aim of this study is to examine the potential of integrating trees in small scale coffee agroforestry systems in three villages on Mount Elgon, as a means to improve carbon sequestration and storage through the accumulation of aboveground biomass (AGB) and improve the aggregate structure and stability of the soil. The study is based on field measurements of tree density and diversity, height, and diameter at breast height, which forms the foundation for estimating AGB using six different allometric models. Additionally, the content of water-stable aggregates (WSA) in the soil is analyzed as an indicator for soil stability, and semi-structured interviews were carried out to shed light on the perspectives of local coffee farmers on soil erosion, tree species preferences, and perceived ecosystem services and benefits from shade trees.

The results revealed an overall low diversity and density of shade trees in the coffee gardens and a widespread preference among farmers for planting exotic tree species over native species. However, many of the farmers expressed an interest in planting more trees, including native species, to improve shade and soil health in the coffee gardens and to generate additional income. Tree density was found to have a positive effect on the WSA percentage in the soil, whereas more frequent digging to remove weeds and manure application had a negative on WSA formation. The allometric models displayed a large degree on variation in AGB estimates, depending on the model used, which underscores the need for allometric models, that are adapted to agroforestry and local environmental/ growing conditions.

The study shows that agroforestry holds a large, untapped potential for increasing the resilience of coffee cultivation systems on Mount Elgon against climate change and soil erosion. To fully realize this potential, it is necessary to adapt the species recommendations to local conditions as well as the needs of local coffee farmers and promote management practices that support soil stability and carbon storage. Thereby, agroforestry can play a key role in the future of sustainable coffee cultivation in the highlands of Eastern Uganda.

1. Background

This thesis is written in affiliation with the project Agroforestry for People, Ecosystems, and Climate (AFPEC) based in Mount Elgon, Eastern Uganda. The project is a collaboration between between Aarhus University, Denmark, Makerere University, Uganda, and Copenhagen University, Denmark with support from the NGOs, Seniors Without Borders, Denmark, Joint Efforts to Save the Environment (JESE), and Youth Leading Environmental Change (YLEC), and funded by the Danish International Development Agency (DANIDA). The objective of AFPEC is to document the effects of agroforestry in terms of ecosystem services and livelihood benefits, to uncover the potential of agroforestry as a climate adaptation and mitigation strategy, as well as a tool to prevent biodiversity loss.

Soil samples and field data were collected in three villages on Mount Elgon, Eastern Uganda. The main objectives of this study were to assess **(1)** the status regarding the tree density and species composition of coffee gardens, **(2)** above ground biomass accumulation using multiple allometric models, **(3)** soil WSA content, and **(4)** farmer perceptions of erosion, agroforestry practices, and desired tree species and ecosystem benefits.

By integrating ecological data with farmer perspectives, the study seeks to contributes to a more comprehensive understanding of how small scale coffee-forestry systems can support climate change, soil health/ stability, and sustainable rural development in a vulnerable mountain ecosystem/ environment.

2. Climate, vegetation, and hydrology

Mount Elgon is a 4,321 m high solitary extinct shield volcano located on the border between Uganda and Kenya. The area is characterized by a tropical montane climate, with bimodal rainfall occurring from March to May and from September to November (Knapen et al., 2006; Sassen et al., 2013). The annual precipitation ranges from 1,500 to 2,200 mm, and the mean monthly temperature varies between 15°C and 25°C, with fluctuations depending on the altitude (Jiang et al., 2014; Wanyama et al., 2021). The slopes of Mount Elgon are overall gentle with an average slope of around 4°. However, the lower lying north and west facing slopes exhibit a stepped topography, which includes areas with cliffs that reach heights of more than 300 m (Sassen, 2014; Sassen et al., 2013).

Three distinct vegetation zones are found on Mount Elgon, an afroalpine and ericaceous zone (moorland and heathland zone), which descends into an afromontane forest zone and an afromontane rainforest zone below (Sassen, 2014). The moorland and heathland zones are composed of bogs, shrub- and grasslands, which includes endemic species such as *Lobelia elgonensis, Alchemilla elgonensis,* and *Senecio elgonensis*. The afromontane forest zone consists primarily of species such as *Podocarpus milanjianus*, *Prunus africana*, and *Hagenia abyssinica* as well as large bamboo forests (*Arundinaria alpina*) (Sassen, 2014; Ssali et al., 2023). Fires on the moorlands play a role in shaping the upper forest boundary (Hamilton & Perrott, 1981; Sassen, 2014). Only small patches of Afro-montane rainforest remain due to human activity and agriculture, which together with the Afro-montane forests and moor- and heathlands above form the Mount Elgon National Park.

Mount Elgon is an important water catchment for the Lake Turkwell and Lake Turkana systems, the Lake Victoria Basin, Lake Kyoga, and the Nile Basin, which provide water for millions of people in Uganda and Kenya (Sassen, 2014). The protected forests play a crucial role in stabilizing the mountain slopes and regulating water flow (Sassen et al., 2013), and the hydrology of the lower lying slopes on Mount Elgon are highly dependent on the integrity of the upstream forests, making the people on Mount Elgon highly vulnerable to forest degradation.

3. Land use and coffee agroforestry

The landscape on Mount Elgon has been significantly shaped by human activities and agriculture over centuries, with a long history of forest clearance, settlement expansion, and smallholder cultivation (Mugagga et al., 2012b; Opedes et al., 2022; Sassen, 2014). The lower mountain slopes are dominated by smallholder farms cultivating crops, such as Arabica coffee, bananas (Matoke), maize, and beans (Opedes et al., 2022; Sassen, 2014). Coffee agroforestry or coffee-banana agroforestry have emerged as key land use systems in the region, where Arabica coffee (*Coffea arabica*) is typically grown under the partial shade of both indigenous and exotic species, such as *Cordia africana, Grevillea robusta, Albizia coriara,* and several different Ficus species (Opedes et al., 2022; van Asten et al., 2011). While these systems offer important ecosystem services such as erosion control, improved soil fertility, and biodiversity conservation, these benefits are often undermined by an increased dominance of exotic tree species and high pressures on tree planting and existing trees due to loss of native forests, lack of space and access to native tree seedlings, and a need for firewood and income (Banana et al., 2014; Buyinza et al., 2022; Sassen et al., 2013; Wagner et al., 2019).

4. Major changes and challenges on Mount Elgon

Human population growth and land scarcity: Mount Elgon has experienced steady and significant human population growth over the past century, contributing to increasing land scarcity and rising pressure on natural resources in the region (Banana et al., 2014; Sassen, 2014). Historically, the fertile volcanic soils and favorable climate for cultivation attracted farming communities to the mountain, leading to widespread settlement, especially on the lower and mid-elevation slopes (Sassen, 2014). Since the 1960s, the region has witnessed a sharp rise in population density due to natural growth and resettlement of people displaced from the more densely populated lowlands (Knappen et al., 2006; Sassen et al. 2013). This has resulted in the subdivision of landholdings across generations, making farm sizes progressively smaller and intensifying land use in already fragile areas (Mugagga et al., 2012b; Wanyama et al., 2021). With limited arable land remaining, more intensive cultivation has extended onto steep slopes and marginal areas, often exceeding recommended slope thresholds for sustainable farming (Knapen et al., 2006; Mugagga et al., 2012b). The increasing scarcity of land has led to conflicts between agricultural expansion and conservation efforts and slope preservation, significantly complicating sustainable land management practices in the region (Sassen, 2014; Sassen et al., 2013).

Deforestation: The population growth and agricultural expansion as well as timber extraction, and weak enforcement of conservation policies in the region has caused Mount Elgon to undergo several decades of extensive deforestation (Banana et al., 2014; Sassen, 2014; Sassen et al., 2013). Historically, the montane forests of Mount Elgon have provided vital ecosystem services to local communities, including firewood, construction materials, medicinal plants, and fertile soils (Sassen, 2014). However, since the 1970s, rising population densities and land scarcity has prompted wide-spread clearing of forests for subsistence farming and settlement, particularly on the lower slopes and in the park buffer zones (Sassen et al., 2013; Mugagga et al., 2012b). Changes to the legal status and defined boundaries of Mount Elgon National Park in the 1990s further complicated land tenure arrangements, leading to tensions between conservation authorities and local communities, some of whom resisted eviction and continued farming within areas that had been newly designated as protected forest (Banana et al., 2014). By the early 2000s, satellite imagery and land cover studies revealed a sharp decline in forest cover, especially in high-risk erosion zones (Opedes et al., 2022). In addition to clearing for crops, the growing demand for fast-growing species such as eucalyptus has accelerated forest degradation, often replacing diverse native forests with monoculture plantations of limited ecological value (Graham et al., 2022; Wagner et al., 2019). This ongoing deforestation has critically undermined slope stability, biodiversity, and watershed function in the Mount Elgon ecosystem (Knapen et al., 2006; Mugagga et al., 2012b).

Climate change: Rising temperatures, shifting rainfall patterns, and an increase in the frequency and intensity of extreme weather events, such as intense rainfall and prolonged dry spells, have been observed over the recent decades in Mount Elgon (WMO, 2023; Jiang et al., 2014). The high dependence of the local population on rain-fed agriculture, combined with growing land scarcity and environmental degradation, has made communities especially vulnerable to these climate-related stresses (UBOS, 2007; Banana et al., 2014). In coffee-producing areas, unpredictable rainfall and temperature fluctuations have disrupted flowering and fruit development cycles, leading to reduced yields, and increased economic insecurity for smallholder farmers (Opedes et al., 2022; Sassen et al, 2013). As a result, there is a growing recognition of the need for climate-resilient agricultural practices, such as agroforestry, that can buffer these climatic extremes while enhancing ecosystem services and long-term sustainability (Banana et al., 2014).

Slope destabilization, and landslides: Mount Elgon's high rainfall (ranging from 1,500 to 2,200 mm annually) combined with its porous volcanic soils and steep slopes, creates a naturally unstable terrain, even on relatively gentle inclines (Knapen et al., 2006; Mugagga et al., 2012a). This instability is worsened by the deforestation and land-use changes in the region, such as cultivation on steep slopes and excavation for house construction, which have been identified as major preparatory factors for landslides (Mugagga et al., 2012b). Bududa has experienced some of the most devastating landslides in recent history, including catastrophic events in 2010 and 2012, with previous major landslides recorded in 1933, 1964, 1970, and 1997(Knapen et al., 2006; Mugagga et al., 2012b).
In recent years, a 40-kilometer crack, widening between 30 and 35 cm, has developed in parts of the region, raising concerns over further large-scale slope failures (Mugagga et al., 2012b).

5. The importance of shade trees in agroforestry

Shade trees play an important role in the agronomic and ecological function of coffee-forestry systems on Mount Elgon because Arabica coffee (*Coffea arabica*), the dominant cash crop for smallholders in the region, is naturally adapted to growing in the semi shade from forest canopies (Gram et al., 2018; Lugo-Pérez et al., 2023; Mayorga et al., 2022; van Asten et al., 2011). Integrating shade trees into coffee cultivation systems serves to mimic these natural growing conditions but can also enhance overall the sustainability and resilience of coffee farming in the fragile, steep landscapes on Mount Elgon. Integrating well-managed shade trees into coffee systems offers multiple ecological and socio-economic benefits, including microclimate regulation carbon sequestration, soil health improvement, and diversified farmer livelihoods, as farmers can also rely on shade trees for services such as food, firewood, construction materials and income generation (Lugo-Pérez et al., 2023; Ortiz-Ceballos et al., 2020; Panwar et al., 2022; Tschora & Cherubini, 2020; Tumwebaze & Byakagaba, 2016; Zake et al., 2015). Van Asten et al. (2011) and Tumwebaze and Buyakagaba (2016) showed that agroforestry systems store more soil organic carbon (SOC) than monoculture systems, especially in topsoil layers. Higher SOC and litter inputs from trees can enhance the microbial activity and the formation of water-stable aggregates (WSA), reducing erosion and runoff (Chemeda et al., 2022; Ehrenbergerová et al., 2016).

Farmers on Mount Elgon commonly use tree species such as *Albizia coriaria, Cordia africana,* and *Ficus natalensis,* which are valued for providing multiple different ecosystem services, particularly shade provision, soil fertility enhancement, and erosion control (Graham et al., 2022; Gram et al., 2018; Wagner et al., 2019). The way the farmers prioritize these services can vary with elevation, as farmers with land located at lower altitudes have been shown to place greater value on shade and soil fertility due to higher temperatures and more severe soil degradation on lower altitudes than on higher altitudes, while farmers at higher altitudes tend to place more value on firewood and timber (Gram et al., 2018). The dominance of exotic species such as *Eucalyptus* sp., *Persea americana,* and *Grevillea robusta*, over native species, found in the present study as well as previous studies, due to their perceived rapid growth and economic return, raises serious ecological concerns (Graham et al., 2022; Gram et al., 2018; Wagner et al., 2019). Graham et al. (2022) found that exotic species over-whelmingly outnumber indigenous trees in agroforestry systems found on Mount Elgon, which limits the benefits of these systems in terms of improving biodiversity and overall ecological resilience. Indigenous trees are valued by local farmers for their ecosystem benefits, but have still become less utilized due to limited knowledge and decreased access to native tree seedlings for farmers. Promoting native tree species is essential for biodiversity conservation and long-term ecosystem functionality (Graham et al., 2022; Wagner et al., 2019).

Farmer's experiences with shade trees are mixed. Buyinza et al. (2022) noted that while most farmes recognize the benefits of shade for coffee production, some also associated shaded environments with increased incidence of coffee diseases, particularly coffee leaf rust. However, this was often linked to poor shade management, such as overcrowding and inadequate pruning. Farmers with more training demonstrated more effective species selection, pruning practices, and understanding of tree-crop interactions (Buyinza et al., 2022). This shows the importance of improving the accessibility and availability of knowledge sharing and training programs for farmers. Farmers' willingness to plant and maintain shade trees is influenced by factors such as institutional support, perceived effort, and local norms (Shebuliba et al., 2022). Facilitating access to seedlings technical guidance, and community-driven demonstration plots is likely to improve the adoption of sustainable agroforestry practices. Aligning species recommendations with farmer-identified needs, while promoting native biodiversity, could be key to realizing the full potential of coffee-forestry (Buyinza et al., 2022; Graham et al., 2022; Gram et al., 2018; Sebuliba et al., 2023; Wagner et al., 2019).

6. Estimating aboveground biomass and carbon sequestration

The long-term carbon sequestration potential of agroforestry systems has been incorporated in Uganda's national climate strategies for climate adaptation and mitigation (Banana et al., 2014). Tumwebaze and Byakagaba (2016) found that Arabica coffee agroforestry systems in Uganda with non-native fruit trees, such as *Artocarpus heterophyllus* and *Mangifera indica,* stored around 54.5 t C/ ha as SOC in the top 30 cm of soil, and similar studies of coffee agroforestry systems in Ethiopia found that the average total biomass carbon stock across different altitudes was around 40.6 t C/ha (Chemeda et al., 2022). However, the overall effectiveness of coffee-forestry as a strategy for climate adaptation and mitigation on Mount Elgon as well as the eligibility of local coffee farmers to participate in voluntary carbon markets, depends on the ability to accurately estimate aboveground biomass (AGB) and carbon storage across a range of different climatic, environmental, system specific, and management related conditions (Chemeda et al., 2022; De Beenhouwer et al., 2016; Ehrenbergerová et al., 2016; Flor-Vélez et al., 2024; Häger & Avalos, 2017). This requires reliable, context-appropriate allometric models that accurately reflect the variability in species composition, growth patterns, and growing conditions found in coffee agroforestry systems.

AGB is commonly estimated using allometric models, which are equations that use easily measurable tree variables, such as diameter at breast height (DBH), tree height, and wood specific density (ρ) to estimate the total aboveground biomass (AGB). These models can be context and/ or species specific or generalized, such as the pantropical equations that are made to estimate AGB in a broad range of tropical forests all over the world (e.g. Chave et al. (2014) and Brown et al. (1997). Studies have reported a broad range of AGB estimates depending on the agroforestry system and allometric models used. Ehrenbergerova et al. (2016) found that AGB estimates ranged between 60.6 t/ha and 124 t/ha for different types of coffee agroforestry systems on tropical sites in Villa Rica, Peru, whereas the ABG for unshaded coffee was around 1.9 t/ha. In the present study, six allometric models were applied to the same set of field measurements to assess the variability and sensitivity of the AGB estimation methods in the context of coffee agroforestry systems on Mount Elgon. The results showed a significant variation in estimated AGB values, both at the tree level and across garden plots and the three villages. The mean AGB per garden ranged between 22.6 t/ha in Bufumbo and 60.2 t/ha in Bududa after outliers had been removed, with Sipi showing a mean AGB of 32.4 t/ha, which is higher than the AGB found for unshaded coffee by Eherenbergerova et al. (2016).

7. Soil aggregate stability and health

Soil aggregate stability is a key indicator of soil health (Barthès & Roose, 2002; Nciizah & Wakindiki, 2014). Water-stable aggregates (WSA) are clumps of soil consisting of silt, sand and clay particles bound together by organic material tightly enough to resist breakdown when exposed to water (Figure 7.1). WSA play an important role in maintaining the water infiltration and water holding capacity of the soil, reducing runoff, and supporting root development (Barthès & Roose, 2002; Nciizah & Wakindiki, 2014; Sui et al., 2012). Therefore, WSA content in the soil is an important indicator of the structural stability of the soil and the ability of the soil to sustain plant growth. In agroforestry systems, trees contribute to WSA formation by increasing the input of organic material (OM) to the soil and supporting microbial activity that helps bind soil particles together to form aggregates (Oyana et al., 2015). In the present study, a significant positive correlation was found between tree density and WSA percentage in the soil across the three study sites, suggesting that higher tree cover supports improved soil structure. This supports the findings of previous studies, which showed that shade threes improved soil structure adding OM and storing more carbon in the soil (Ehrenbergerová et al., 2016; Flor-Vélez et al., 2024; Oyana et al., 2015; Solis et al., 2020). On the other hand, more frequent digging to remove weeds, and manure application was associated with lower WSA formation in the soil, likely due to physical disturbance of the soil and imbalances in microbial growth and activity as result of the manure application leading to a breakdown of organic carbon (OC) in the soil (Knapen et al., 2006; Lin et al., 2019; Mugagga et al., 2012a; Sassen et al., 2013; Sui et al., 2012).

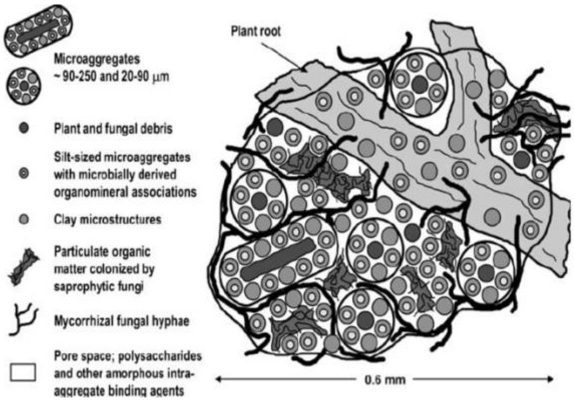

Figure 7.1: *Conceptual diagram of aggregate structure and hierarchy illustrating microaggregates inside a macroaggregate (Jastrow et al., 2007).*

8. Carbon credits and climate inequality

Carbon credit programs are increasingly being explored as a mechanism to incentivize smallholder farmers in Uganda to plant trees and adopt more sustainable land management practices, as they offer payment to farmers for implementing sustainable management practices, such as tree planting (Tumwebaze & Byakagaba, 2016). Although, carbon credit programs can provide a meaningful incentive for some farmers to plant more trees in their coffee gardens, as demonstrated by pilot initiatives in East Africa, such as Trees for Global Benefits (TGB) Uganda, and Internnational Small

Group and Tree Planting Program (TIST) (Shames et al. 2012), they also raise concerns regarding equity and effectiveness. A key criticism is that carbon credit programs risk contributing to greater climate inequality, as smallholders in the Global South are expected to generate carbon offsets for emissions primarily produced in the Global North, often for limited financial returns and with little control over market terms (Fairhead et al., 2012; Carton & Andersson 17; Purdon, 2015; Westoby & Lyons, 2016). Moreover, farmers on Mount Elgon face problems with land scarcity and increasing food insecurity and reliance on land for subsistence farming, which negatively affects their ability to dedicate space to trees for carbon storage alone (Opedes et al., 2022; Sassen, 2014; Sassen et al., 2013; Sebuliba et al., 2023). Therefore, it is important that national and global policies regarding carbon credits focus on also safeguarding the farmers' interests to avoid reinforcing these power imbalances, excluding vulnerable farmers, and reducing local autonomy over land use decisions (Fairhead et al., 2012; Shames et al., 2012).

9. Prospects for climate mitigation and environmental conservation

The present study examined the potential role of coffee agroforestry systems in contributing to climate mitigation and environmental conservation in the Mount Elgon region of Eastern Uganda. By quantifying AGB accumulation, evaluating soil aggregate stability (WSA), and defining the current state in terms of management, tree density, and species composition/ diversity, the study provides empirical data that can serve as a foundation for the future development of more site-specific, climate-smart, and resilient land management practices. The integration of farmer perceptions and species preferences aims to strengthen the applicability of these results to real-world sustainable agroforestry system development and local implementation in areas such as Mount Elgon.

The moderate AGB stock estimates found across all gardens, despite many garden plots showing a low tree density and species diversity, indicates a solid potential for carbon sequestration at the smallholder scale, especially if practices of increased tree planting and species diversification are implemented. The variation in AGB estimates across the six different allometric models in this study highlights the need for developing more locally tailored models adapted to the context of agroforestry, which could significantly improve the precision and accuracy of AGB and carbon stock assessments (Chave et al., 2014; Segura et al., 2006; Tumwebaze et al., 2013). The demonstration of a clear, positive relationship between tree density and soil structural health (based on WSA analysis), shows that that the shade trees play a role in improving the health and structural stability of the soil, which is likely related to carbon sequestration in the soil (Ehrenbergerová et al., 2016; Flor-Vélez et al., 2024; Oyana et al., 2015; Solis et al., 2020).

The observed interest among farmers in planting more trees, including native species, and in ecosystem services such as shade provision and improved soil health and stability, shows a strong opportunity for more conservation focused agroforestry interventions.

Future research can build on these findings in several ways. First, there is a need for further calibration and validation of allometric models specific to local tree species and the growing conditions in coffee-agroforestry systems on Mount Elgon. Second, long term monitoring of WSA and soil carbon dynamics in relation to tree species composition, density, and management practices can provide valuable data on the effects on soil health and stability over time, which is key to evaluating the long-term sustainability of these systems. Lastly, adapting the species recommendations to local conditions as well as the needs of local coffee farmers and promoting management practices that support soil stability and carbon are key to fully realize the potential of agroforestry for climate mitigation and environmental and ecological conservation.

10. Conclusion

This study contributes to a growing body of evidence supporting agroforestry as sustainable strategy for climate mitigation, environmental conservation, and increased farming system resilience against climate variability in rural East African highland communities such as the coffee farming villages on Mount Elgon. In the present study, the mean AGB per garden ranged between 60.2 t/ha in Bududa and 22.6 t/ha in Bufumbo after outliers had been removed, with Sipi averaging AGB of 32.4 t/ha. The average WSA percentage per garden ranged from 46.9% ± 5.8% (SE) in Bufumbo to 72.6% ±1.8% (SE) in Sipi. The WSA percentage in the soil varied across sites, and was significantly influenced by tree density, weed digging frequency, and manure application frequency. These results highlight a need for further calibration and validation of allometric models specific to local tree species and the growing conditions in coffee-agroforestry systems on Mount Elgon. Providing farmers with support for selecting appropriate species, could enhance tree density, diversity, AGB formation and carbon sequestration as well as WSA formation, leading to more productive systems and less soil erosion.

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12. Article Manuscript

Aimed for *Agroforestry Systems*

Foto: Emilie Ellesoe Nielsen and three local children walking next to a large erosion scar between two garden plots in Sipi, Uganda (October 2024)

The Potential of Shade Trees for Biomass Accumulation, and Soil Stability in Coffee Agroforestry Systems on Mount Elgon, Uganda

Mathilde Willemoes

Abstract

Arabica coffee (*Coffea arabica*) is a key crop for smallholder farmers on Mount Elgon, Eastern Uganda, but its production is increasingly challenged by soil degradation, climate variability, and erosion. Coffee agroforestry systems, which integrate shade trees with coffee cultivation, offer potential to improve ecosystem goods and services through increased biodiversity, enhanced carbon sequestration, improved soil health and supplementary useful products. This study aims to assess the potential of trees in smallholder coffee agroforestry systems in three villages on Mount Elgon, Bududa, Bufumbo, and Sipi, for improving carbon sequestration through above ground biomass (AGB) accumulation, and soil structural stability. Field data were sampled and used to determine the species composition of shade trees and estimate AGB using six different allometric models. Soil structural stability was assessed through an analysis of soil water-stable aggregate (WSA) content, and semi structured interviews were conducted to explore farmers' perceptions on soil erosion, and species- preferences and benefits. An overall low tree density and diversity was found, as farmers preferred planting exotic tree species over native species and overall favored a few select species, such as *Eucalyptus* sp., *Persea americana,* and *Cordia africana*. However, there was a clear interest among farmers in planting more trees, including native species such as various *Ficus* and *Albizia* species. Farmers valued ecosystem services, such as shade, soil fertility and income generation highly. AGB estimates varied widely depending on the models used and among garden plots. The mean AGB per 100 m^2 garden ranged between 602 kg in Bududa and 226 kg in Bufumbo after outliers had been removed, with Sipi showing a mean AGB of 324 kg. The average WSA percentage per garden ranged from 46.9% ± 5.8% (SE) in Bufumbo to 72.6% ±1.8% (SE) in Sipi. Higher tree density was positively associated with WSA, while frequent digging and manure application had a negative effect on soil WSA formation. There is an untapped potential of agroforestry to enhance climate and functional resilience in smallholder coffee cultivation systems. Aligning tree species recommendations with farmer preferences and site-specific conditions can support both environmental and livelihood goals.

Key words: Coffee agroforestry, Mount Elgon, carbon sequestration, allometric models, soil aggregation, smallholder farming, farmer knowledge and perceptions.

Introduction

Coffee production plays an important role in Uganda's national economy and rural livelihoods. In 2022, Uganda exported around 298,000 tonnes of green coffee at a value of approximately 754 million USD, making coffee the country's most important agricultural export by volume and revenue (FAOSTAT, 2022). In Uganda, nearly 42% of farming households are engaged in coffee cultivation (UCDA, 2015), with 90% of coffee producers being smallholders managing less than three hectares of land Gram et al. (2018). Most of the coffee in Uganda is grown in agroforestry systems, which incorporate bananas (Matoke) and shade trees (van Asten et al., 2011). The majority of the Ugandan population remain dependent on rain-fed agriculture, making rural livelihoods, including those of coffee farmers, highly vulnerable to climate variability and extreme weather events, which are becoming increasingly frequent and severe due to the effects of climate change (WMO, 2023; UBOS, 2007). For the coffee farmers on Mount Elgon frequent occurrences of landslides and extreme, unpredictable precipitation events in the region have significantly reduced coffee yields in some years and left farmers with very little income (Jiang et al., 2014; Mugagga et al., 2012b; Opedes et al., 2022; Sassen, 2014; Sassen et al., 2013). Recognizing the strategic importance of coffee, the Ugandan government aims to double national coffee production by 2040 and promote coffee agroforestry, which integrates trees into the coffee cultivation systems, as a key strategy to achieve this goal sustainably (UCDA; 2015; Banana et al., 2014).

Agroforestry systems have been identified as one of the most promising solutions for addressing both climate change and land degradation in Uganda, especially in vulnerable highland regions, such as Mount Elgon, where landslides are becoming more frequent due to climate change, high population pressures and deforestation (Jiang et al., 2014; Knapen et al., 2006; Mugagga et al., 2012a, 2012b; Sassen, 2014; Sassen et al., 2013).The practice of integrating trees with coffee cultivation provides not only shade for the coffee plants, but a range of ecosystem services, such as increased carbon seques-tration and storage, and enhanced soil health. Hence, agroforestry offers the potential to increase the resilience of coffee cultivation systems to climate change by increasing the biodiversity, supporting biomass production and carbon sequestration, and improving soil structure (Lugo-Pérez et al., 2023; Ortiz-Ceballos et al., 2020; Panwar et al., 2022; Tschora & Cherubini, 2020; Tumwebaze & Byakagaba, 2016; Zake et al., 2015). In Mount Elgon, many smallholders have begun integrating more trees into their coffee gardens not only for shade and soil stabilization, but also to reduce dependency on natural forests and diversify income sources (Banana et al., 2014). Over the years, encroachment on natural forests around the perimeters of Mount Elgon Natural Park, has significantly limited the farmers' access to native tree species, that they were previously very reliant on (Opedes et al., 2022; Sassen et al., 2013; Sebuliba et al., 2023).

Despite a growing interest for coffee-forestry systems, a lack of empirical data remains for quantifying biomass accumulation and carbon sequestration potential, and soil related co-benefits, at the smallholder scale in Mount Elgon (Broeckx et al., 2019; Buyinza et al., 2022; De Beenhouwer et al., 2016; Ehrenbergerová et al., 2016; Flor-Vélez et al., 2024; Graham et al., 2022; Gram et al., 2018; Häger, 2012; Häger & Avalos, 2017). Moreover, existing biomass calculations and carbon credit programs are often developed for broader tropical forest contexts, and may not be as accurate for the mixed-species, small scale, intensive coffee-forestry systems found in the region (Chave et al., 2014; Ehrenbergerová et al., 2016; Kuyah et al., 2012; Segura et al., 2006; Tumwebaze et al., 2013). Similarly, farmer attitudes, knowledge, and practices regarding agroforestry remains underexplored, particularly in relation to carbon farming and ecosystem service awareness. This study aims to address these gaps by assessing the carbon storage potential, and effect on soil structure of shade trees in coffee-forestry systems.

Specifically, the study aims to assess the current status regarding the tree density and species composition of coffee gardens, (2) above ground biomass accumulation using multiple allometric models, (3) soil WSA content, and (4) farmer perceptions of erosion, agroforestry practices, and desired tree species and ecosystem benefits. By integrating ecological data with farmer perspectives, the study seeks to contributes to a more comprehensive understanding of how small scale coffee-forestry systems can support climate change, soil health/ stability, and sustainable rural development in a vulnerable mountain ecosystem/ environment.

Materials and Methods

Study area

The study was conducted in Eastern Uganda on Mount Elgon, which is a 4,321 m high solitary extinct shield volcano located at $0^{\circ}52'$-$1^{\circ}25'$ N and $34^{\circ}14'$- $34^{\circ}44'$ E. (Fig. 1). The study sites were located in the villages of Bududa/Bushiyi (1.0105, 34.3334), Bufumbo (1.1419, 34.3506), and Sipi (1.3347, 34.3742) lying at an average altitude of 1,590 m, 1,346 m, and 1,890 m, respectively (Jarvis, 2008). The area is characterized by a tropical montane climate, with bimodal rainfall occurring from March to May and from September to November (Knapen et al., 2006). The annual precipitation ranges from 1,500 to 2,200 mm, and the mean monthly temperature varies between 15°C and 25°C, with fluctuations depending on the altitude (Jiang et al., 2014; Wanyama et al., 2021). The slopes of Mount Elgon are overall gentle with an average slope of around 4°. However, the lower lying north and west facing slopes exhibit a stepped topography, which includes areas with cliffs that reach heights of more than 300 m (Sassen, 2014; Sassen et al., 2013). The average slope of the Bududa, Bufumbo, and Sipi study sites are approximately 16°, 11°, and 12° respectively (Jarvis, 2008). The study area, particularly the Bududa study site, is very prone to landslides, due to the steep slopes, high rainfall, low soil stability and resistance, and extensive land use changes. Soil erosion and deforestation have increased environmental vulnerabilities, impacting agricultural livelihoods in the area (Broeckx et al., 2019; Knapen et al., 2006; Mugagga et al., 2012b). The increasing intensity of rainfall and land-use pressure have heightened the risk of landslides, making disaster management a key concern for local farming communities and policymakers (Claessens et al., 2007; Mugagga et al., 2012b).

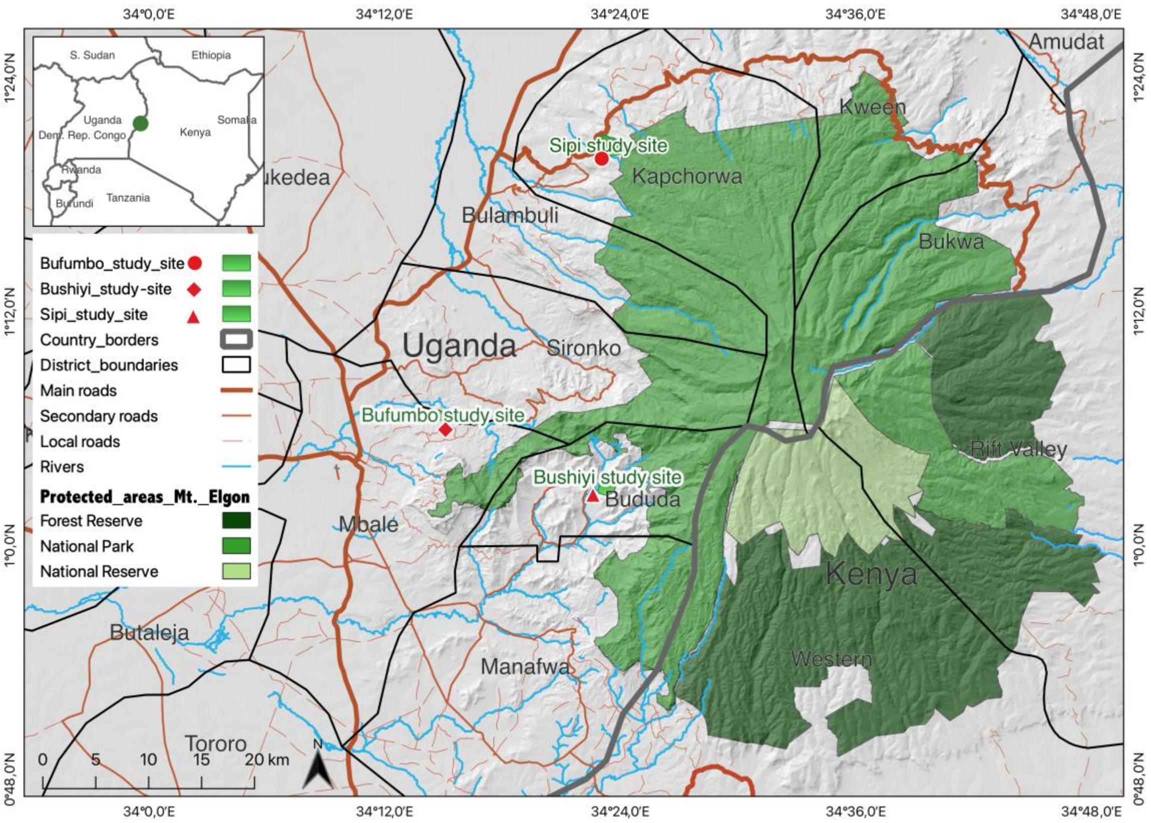

Fig. 1. *Map of the Ugandan and Kenyan side of Mount Elgon with the location of the 3 study sites.*

Land use and coffee agroforestry: The lower mountain slopes are dominated by smallholder farms cultivating crops, such as arabica coffee (*Coffea arabica)*, bananas (matoke), maize, and beans (Opedes et al., 2022; Sassen, 2014). Coffee agroforestry or coffee-banana agroforestry are key land use systems in the region, where arabica coffee*,* mostly grown together with Matoke, is cultivated in the shade from indigenous and exotic trees, such as *Albizia coriaria*, *Cordia africana*, and various *Ficus* species (Opedes et al., 2022; van Asten et al., 2011). This system enhances soil fertility, reduce soil erosion, and provide habitat for biodiversity, while improving the farmer's resilience to climate variability and climate change (van Asten et al., 2011). However, deforestation due to agricultural expansion, timber extraction, land fragmentation, and settlement encroachment has significantly altered the land use patterns, particularly in Bududa, where land degradation has severely increased the potential risk of landslides (Mugagga et al., 2012b). Furthermore, the expansion of eucalyptus plantations has raised concerns about potential water depletion and soil degradation (Sassen et al., 2013). In contrast, conservation efforts around Sipi Falls have promoted ecotourism and served to improve the balance of land use and environmental sustainability (Sassen et al., 2013; van Asten et al., 2011).

Hydrology and history of landslides: Mount Elgon serves as a critical water catchment for major hydrological systems, including the Lake Turkwell, Lake Turkana, Lake Victoria, Lake Kyoga, and the Nile Basins, supporting millions of people in Uganda and Kenya (Sassen, 2014). However, deforestation and intensive land-use changes, particularly the expansion of eucalyptus cultivation, deplete? the mountain's forests and their vital role in water regulation, leading to down-stream impacts on soil and water quality (Sassen et al., 2013; Sassen, 2014). This hydrological vulnerability is worsened by the region's high rainfall (1,500-2,200 mm annually) and porous volcanic soils, particularly in areas with steep slopes (Knapen et al., 2006). Human activities, such as cultivation on steep slopes and excavation, exacerbate this instability, serving as major preparatory factors for landslides (Mugagga et al., 2012). The Bududa District has a history of devastating landslides, with catastrophic events in 2010 and 2012, alongside significant past occurrences in 1933, 1964, 1970, and 1997 (Knapen et al., 2006; Mugagga et al., 2012). The recent development of a 40-kilometer crack further raises concerns about large-scale slope failures (Mugagga, 2011). The Ugandan National Environment Regulations for Mountainous and Hilly Areas Management (Kajura, 2001) prohibiting cultivation on slopes steeper than 15% often remain unenforced in densely populated agricultural areas like Bududa, Bufumbo, and Sipi (Knapen et al., 2006).

Sampling design and data collection

Coffee garden inventory: Field sampling was carried out from start October to mid-December 2024. A total of 25 coffee garden plots and farmers were randomly selected based on a list of farmers provided by the local cooperatives and farming groups. Each farmer was asked to identify their main coffee garden, ensuring that the system was at least one year old to allow for meaningful assessment of tree growth and carbon sequestration. The selected garden plots represented a gradient of tree cover, ranging from low to high, to facilitate modelling of the above ground biomass (AGB) and carbon sequestration based on the density of trees in the garden plots. Each selected garden was treated as a single plot for data collection, and GPS coordinates of the corners of the garden plots were collected using a GPS tracker app for further analysis of garden size, shape, elevation, and slope. The diameter at breast height (DBH, 130 cm) of all trees (>5 cm DBH) within the selected garden plots was measured using a calliper, always measuring from the upper slope side and the tree species was identified. Tree height was estimated based on the line-of-sight method. The specific wood density of the tree species (SWD, ρ) was obtained from the Global Wood Density Database (Zanne et al., 2009).

Management practices, farmer perceptions, and ethnobotanical data: Semi-structured interviews were conducted with 25 participating farmers to gain insight into management practices affecting tree biomass and carbon sequestration and soil conservation. The interviews took place on-site before field measurements to accommodate farmers' schedules, and a local translator was available where necessary. Farmers were asked about maintenance activities such as stumping frequency, fertilizer or manure used and frequency of application, and weed management strategies, distinguishing between digging and slashing methods. Perceptions of soil erosion were recorded by inquiring about the perceived erosion severity and risk in the respective garden plots and observed seasonal variations, particularly during the dry and rainy seasons, and any soil erosion control measures implemented by the farmers. Based on these responses the farmer perceived erosion risk was scored from 0 -2, with 0 being mild erosion and 2 being severe erosion. Finally, tree planting motivations and species preferences were discussed to assess farmers' attitudes toward agroforestry and sustainability.

Soil data

Soil samples were collected from the top 10 cm of soil of 17 of the 25 garden plots included in the study for analysis of water-stable aggregates. The four main corners and the approximate center of each coffee garden were selected as sampling points. A mobile randomizer app was used at each sampling point to (1) determine a random direction and (2) generate a step count (up to ~ 50% of the distance to the center) for locating the exact sampling spot. Soil from the five sampling points were composited into a single sample per garden, placed in paper bags, and stored at room temperature for four months prior to analysis. Water-Stable Aggregate (WSA) stability was used as an indicator of soil structural resilience and erosion resistance (Barthès & Roose, 2002; Nciizah & Wakindiki, 2014). The WSA proportion was measured using the method outlined by Banwart and Sparks (2017). Air-dried samples (40°C, 24 h) were homogenized and three 40 g replicates were drawn in a "W" pattern across the tray surface. Material >2 cm and debris were removed.

Each replicate was manually wet-sieved (based on Elliott, 1986; Loaiza Puerta et al., 2018; into four aggregate size classes: >2000 µm (L), 1000–2000 µm (M), 250–1000 µm (S), and 150–250 µm (XS). Samples were slaked in deionised water for 5 minutes, then sieved with 50, 40, and 30 strokes for decreasing mesh sizes, as appropriate. Aggregates were collected, dried (105°C, 48 h), and weighed.

To correct for sand particles retained during sieving, 5 g subsamples from each fraction were dispersed in 0.5% sodium hexametaphosphate on a rotary shaker (18 h, 190 rpm), then wet-sieved, washed, dried (60°C), and weighed. Sand content was subtracted from the respective aggregate fractions. WSA percentages and size distributions were subsequently calculated.

Data analysis

GPS coordinates marking the boundaries of each coffee garden were digitized to create individual polygon layers from which the individual garden sizes were calculated in QGIS. These were overlaid on a digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM), accessed via the SRTM Downloader plugin in QGIS, which retrieves processed 30 m resolution elevation data from the CGIAR-CSI repository (Jarvis, 2008). A slope raster was generated from the DEM, and zonal statistics were computed for each polygon to extract mean slope and elevation. The analysis of garden slope, elevation, and size was conducted using **QGIS version 3.22.11 Białowieża** and all statistical analysis were conducted using **RStudio version 2025.05.0+496** running **R version 4.4.0**.

The number of trees and the number of unique tree species were calculated per 100 m^2 garden using the garden size estimates. The overall abundance of tree species was determined by counting occurrences across all garden plots. For village-specific relative abundance, species counts within each village were converted to percentages. **Above Ground Biomass (AGB)** for individual trees was estimated using six established allometric models (Table 1). The relationship between AGB estimates and Diameter at Breast Height (DBH) for these models was modelled and visualized using LOESS smooths or Loess regression. The average AGB per tree was calculated across the six models, and total summed AGB per garden was normalized to AGB per 100 m^2. Differences in garden size, elevation, slope, tree density, unique tree species count, native tree species percentage, and AGB per 100 m2 garden among villages were assessed using one-way Analysis of Variance (ANOVA). Garden size, tree density, unique species count, and average AGB were log-transformed (log(x+1) or log(x)) to satisfy assumptions of normality and homogeneity of variance. Model assumptions were verified through Shapiro-Wilk tests and Q-Q plots for residual normality, and Bartlett's tests for homogeneity of variances. Justifiable outliers, identified via standardized residuals were iteratively removed when they significantly affected model assumptions. For significant ANOVA results, posthoc pairwise comparisons were conducted. Descriptive statistics were used to summarize frequencies of various management practices.

Table 1: *Summary of selected allometric models used for estimating above ground biomass (AGB)* (Chave et al., 2005; Chave et al., 2014; Kuyah et al., 2012; Segura et al., 2006; Tumwebaze et al., 2013).

Source	Environmental Conditions	Sites	System	Number of Trees	Species Sampled	DBH Range (cm)	Allometric Equation
Brown. (1997)	Annual rainfall 1,500-4,000 mm. Short to no dry season	Brazil, Indonesia, Cambodia	Tropical, moist broadleaf forest	170	Multi-species	5.0-148	ln(AGB)= exp(-2.134+2.530 x ln(DBH))
Chave et al. (2014)	Pan tropical model adapted to diverse climatological and environmental conditions	58 tropical forest sites in Latin America,	Dry, moist, and wet tropical forests	4004	Multi-species	5.0-150.0	AGB = 0.0673 x (ρ xDBH^2 x H)^0.976
Chave et al. (2005)	Elevation 0-500 m a.s.l.. Annual rainfall 1,800-6,000 mm	Neotropics, South-East Asia, Oceania	Tropical moist forest	1502	Multi-species		AGB = ρ x exp(-1.499 + 2.148 x ln(DBH) + 0.207 x (ln(DBH))2 – 0.0281 x (ln(DBH))3)
Kuyah et al. (2012)	Annual rainfall average 1,000 and 1,800 mm, bimodal, Mean temp. 16.7°C -21.9°C. Elevation 1,200-2,200 m	Yala River basin, Western Kenya	Agroforestry	72	Multi-species	2.5-102	AGB=0.091 x DBH^2.472
Segura et al. (2006)	Tropical highlands. Well distributed rainfall (~2,000 mm/year)	Matagalpa, Nicaragua	Coffee agroforestry	Not specified	Multi-species	5.0-50.0	log10(AGB)= -0.834 + 2.223 x log10(DBH), MSE = 0.02, CF= exp(MSE x Ln(10)^2 / 2)
Tumwebaze et al. (2013)	Elevation 1,250 m a.s.l. Average annual rainfall 1,560 mm (bimodal) Annual minimum 20.8 °C, Annual maximum 25.2 °C	Mukono, Central Uganda	Linear simultaneus agroforestry system	57	Multi-species (Markhamia lutea, Casuarina equisetifolia, Maesopsis eminii, Grevillea	11.4-43.9	ln(AGB)= -0-010 + 1.580 x ln(DBH) + 0.148 x ln(H) + ε, MSE = 0.331, CF = exp(MSE/2)

Water-stable aggregates (WSA%) was analyzed by size class and total mean using ANOVA, excluding Bufumbo from the ANOVA, since it only included 3 different garden plots, and multiple linear regression, incorporating predictors such as tree density and management practices (e.g., digging and manure application frequency). The final model included the parameters tree density, manure application frequency, and digging frequency. AGB and weeding by slashing frequency were initially included in the model but were removed during model simplification due to lack of statistical significance ($p > 0.05$). The final model selection was based on simplification and diagnostic checks, including residual plots, Q-Q plots, and multicollinearity (VIF).

Farmer perceived erosion levels, were scored from 0-2, where 0 = no erosion or mild erosion, only during the rainy season, 1= moderate erosion, mainly during the rainy season, and 2 = severe erosion during the rainy season, and occasional erosion events outside of the rainy season. The frequency in terms of the percentage of garden plots (n=25) receiving each rating by the respective farmers was calculated. Additionally, the frequency (%) of farmers mentioning specific a) **desired tree species** and b) **perceived benefits** from planting the mentioned trees as a percentage of the total number of farmers (n = 23) was calculated counting each species and perceived tree benefit once per farmer.

Results

General characterization of coffee farmers and garden plots

The informants included women (48%) and men (52%). The coffee garden sizes ranged between 0.02 and 0.77 ha, with an average of 0.17 ha. The garden plots in Sipi were on average larger than in Bududa and Bufumbo ($p = 0.007$). No significant difference in garden size was found between Bududa and Bufumbo (Fig. 2a). The average elevation of the garden plots was 1.55, 1.36, and 1.87 km above sea level in Bududa, Bufumbo, and Sipi, respectively (Fig. 2b). The average slope of the garden plots was approximately 10°, with no significant differences between the three villages (Fig. 2c). Overall, the tree densities ranged between 0 and 11 trees per 100 m^2 garden, with an average tree density of 2 trees per 100 m^2 garden with no significant difference between villages (Fig. 2d). On average two different tree species were found per 400 m^2 coffee garden across all garden plots (Fig. 2e). On average 42% of the total number of trees found per garden were native to Uganda and/or the Mount Elgon Region of Uganda specifically with no significant difference found between the study villages (Fig. 2f).

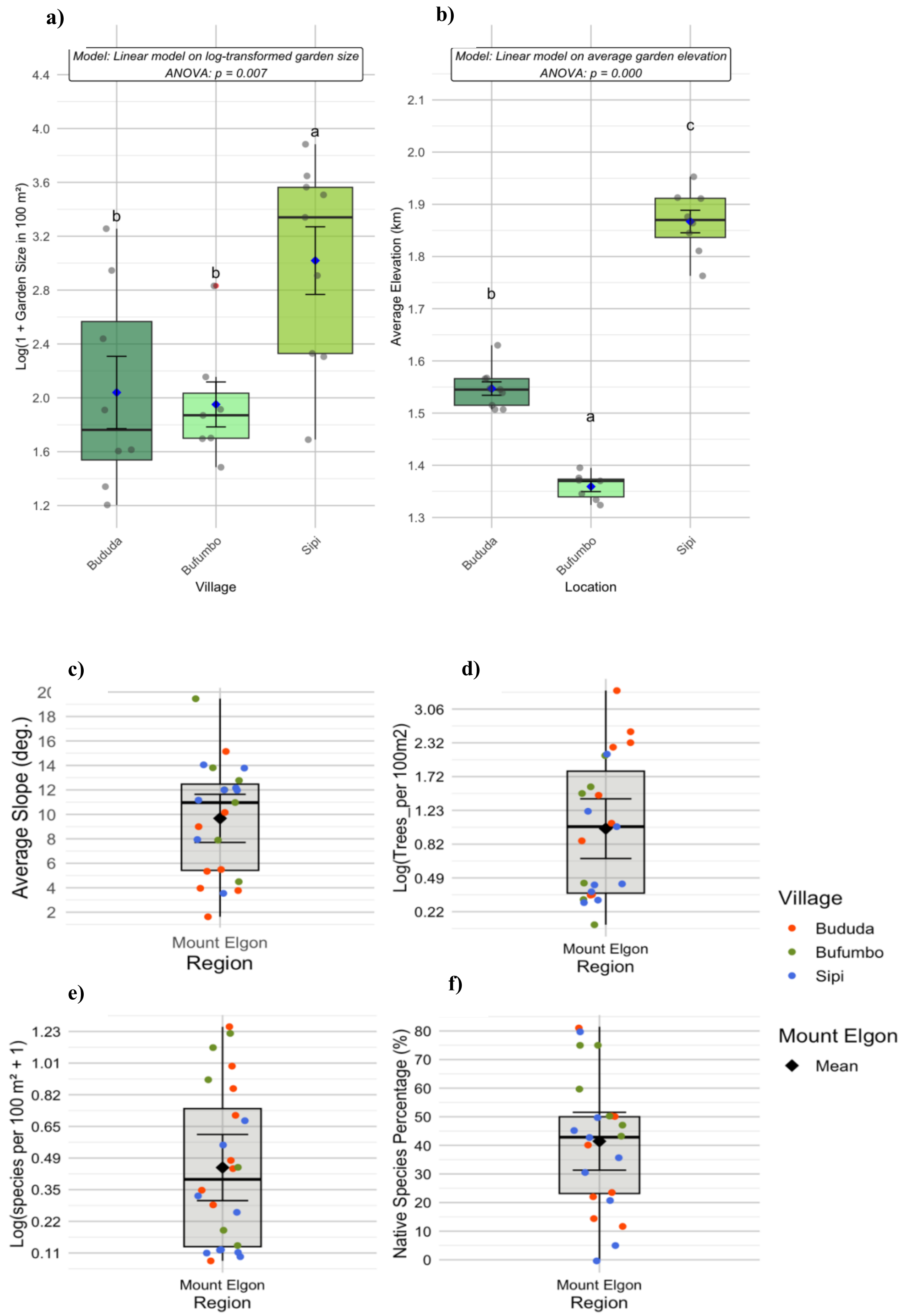

Figure 2: ***a)*** *Log transformed garden size.* ***b)*** *Average garden elevation.* ***c)*** *Average garden slope in degrees for the three study villages combined (Mount Elgon region).* ***d)*** *Log-transformed tree density per 100 m²* ***e)*** *Log-transformed number of unique species per 100 m²).* ***f)*** *Native species percentage relative to the total number of trees per garden). Mean (±SE) and annotations indicating differences between villages based on a post hoc analysis are included.*

Management practices

The informants generally chose to remove weeds by digging in the dry seasons to avoid issues with soil erosion during the rainy seasons, digging on average three times a year. Slashing to remove weeds, leaving the remains on the ground, was done more frequently, around five times a year on average, mainly in the rainy seasons (Table. 2). Manure was applied around three times a year on average with several farmers reporting lacking the necessary tools and means to distribute the manure evenly and as often as they would like in their coffee gardens. The coffee plants were on average stumped every nine years and pruned almost yearly (Table 2).

Table 2: *Summary of the frequencies of various coffee management practices*

Mount Elgon - Frequencies of Management Practices						
Management practice	**Mean**	**SD**	**SE_95_CI**	**Min**	**Max**	**Count**
Digging freq. (per year)	3	1.1	0.4	2	6	25
Slashing freq. (per year)	5	3.8	1.5	0	12	25
Manure appl. freq. (per year)	3	2.1	0.8	1	12	25
Pruning interval (years)	1	0.4	0.2	0	2	25
Stumping interval (years)	9	4.5	1.9	4	20	22

Tree species diversity and composition

A total of 31 different tree species were identified across the 25 garden plots, of which 45% were native species. The most abundant tree species were *Eucalyptus globulus* followed by *Cordia* sp. (which includes *C. africana* and *C. milenii*), and *Persea americana* (Table 3). Of the 15 most abundant species, about 33% were native species. *Cordia.* sp. was the most frequently encountered species, found in 64% of all garden plots. In contrast *Eucalyptus globulus* was only found in 36% of the garden plots. Looking at the top 15 tree species in terms of abundance, it is evident that a select few species dominate, particularly for the native trees, which are dominated by *Cordia* sp., *Markhamia lutea*, and *Ficus natalensis*.

Table 3: *Top 15 most abundant species from the Mount Elgon study villages.*

Mount Elgon - Top 15 most abundant tree species					
Rank	Latin name, species	Native (N)/ Exotic (E)	Total number	% of garden plots	% of total trees
1	*Eucalyptus globulus*	E	112	36	27.2
2	*Cordia sp.*	N	72	64	17.5
3	*Persea americana*	E	27	52	6.6
4	*Markhamia lutea*	N	26	28	6.3
5	*Eucalyptus grandis*	E	22	20	5.3
6	*Eucalyptus camaldulensis*	E	18	12	4.4
7	*Grevillea robusta*	E	18	28	4.4
8	*Artocarpus heterophyllus*	E	14	20	3.4
9	*Mangifera indica*	E	12	28	2.9
10	*Ricinus communis*	E	12	12	2.9
11	*Ficus natalensis*	N	11	20	2.7
12	*Croton macrostachyus*	N	9	24	2.2
13	*Pinus patula*	E	8	4	1.9
14	*Acrocarpus fraxinifolius*	E	7	8	1.7
15	*Maesopsis eminii*	N	7	4	1.7

The Eucalyptus trees were mostly placed near and around the borders of the garden plots, but some were also found inside. When, excluding the Eucalyptus species *Cordia* sp. was found to be the most abundant species on all three locations, ranging from a relative contribution of 15% of the total number of trees in Bufumbo to 37% in Sipi (Fig. 3). The other 7 most abundant species varied between the villages (Fig. 3).

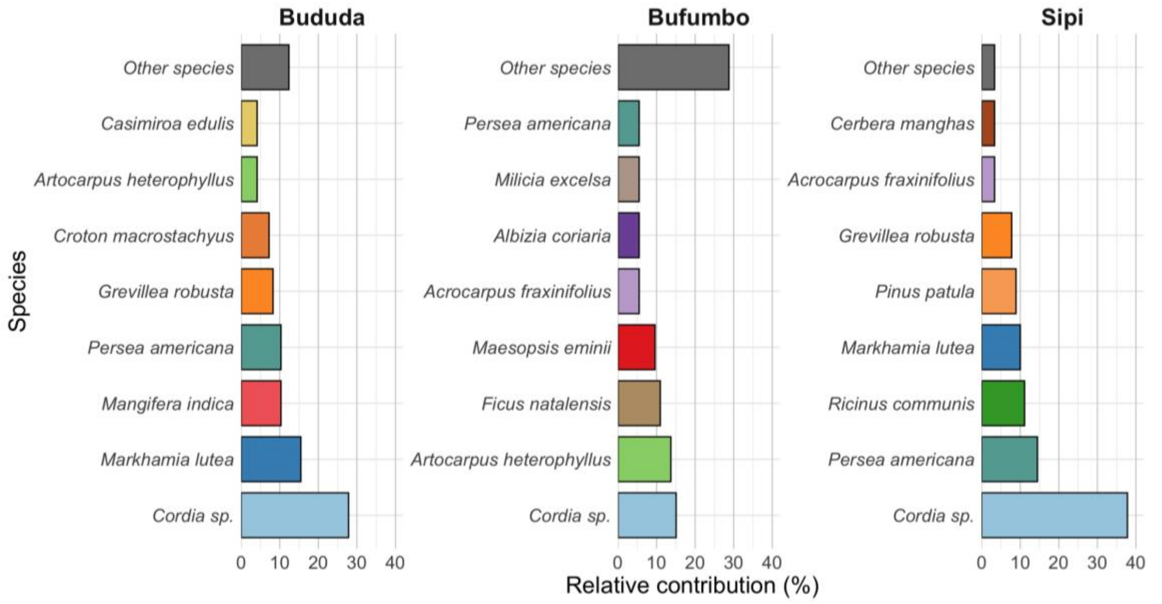

Figure 3: *Relative percentage (%) contribution in terms of total number of trees in the village of the 8 most abundant species (excluding Eucalyptus* sp.*) in the three study villages.*

Above ground biomass and carbon storage

The six allometric models used to estimate AGB showed some variation based on a fitted relationship between AGB and $DBH_{1.3m}$ using Loess regression (Fig. 4). Chave (2005), Brown, and Chave (2014) estimated AGB per tree in the range of 2000-2350 kg at $DBH_{1.3m}$ of 50 cm, Kuyah estimated 1400 kg, and Tumwebaze and Segura estimated around 900 kg. Overall, the estimated AGB of trees with a $DBH_{1.3m}$ of 50 cm varied between 900 and and 2350 kg based on the fitted relationship between AGB and DBH. The difference between the highest and lowest AGB estimate increased along with increasing $DBH_{1.3m.}$ All models showed high statistical significance ($p < 0.001$), indicating that the observed relationships between DBH and AGB are not due to chance (Fig. 4). All models showed a strong or very strong fit based on the R^2 value, apart from Chave (2014), which showed a more moderate fit ($R = 0.72$) (Fig. 4). The Tumwebaze and Segura showed the highest fit explaining 97% and 92% of the variance in AGB respectively.

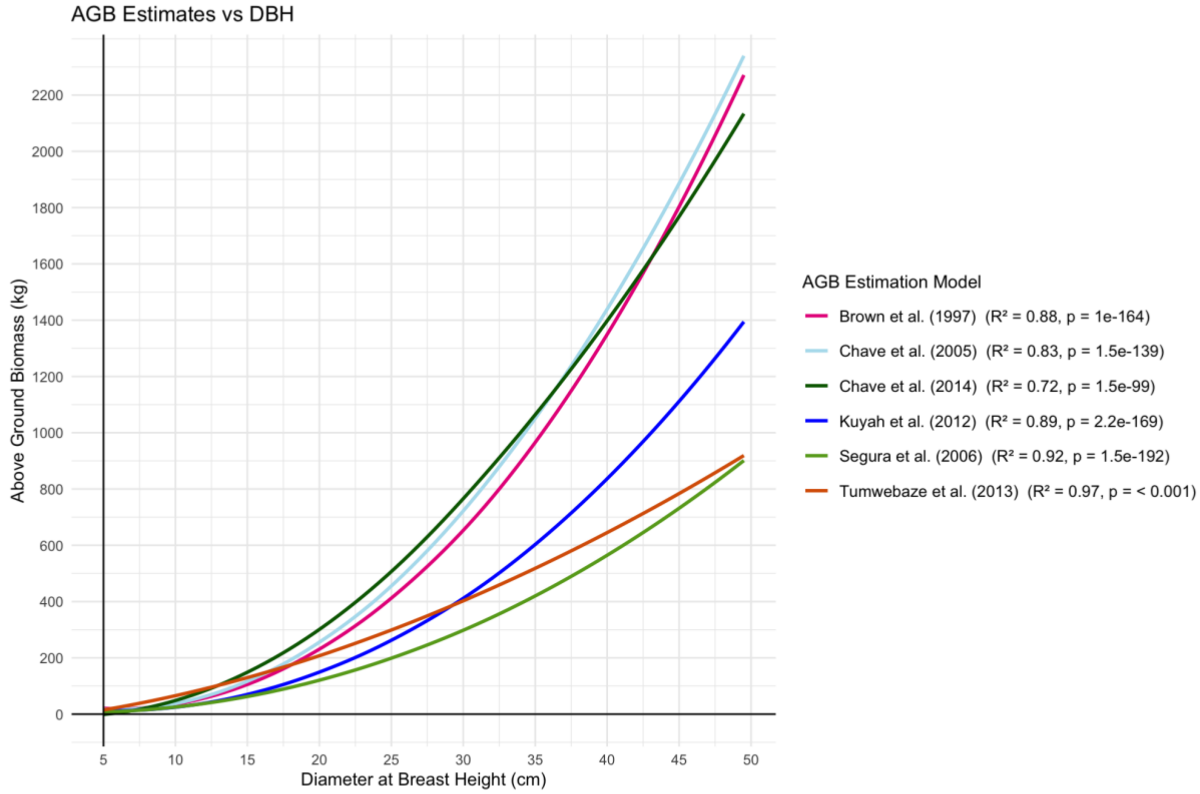

Figure 4: *Relationship between AGB (kg) estimates and $DBH_{1.3}$ for six selected allometric models with R^2 and P-values for each model.*

Overall, mean estimated AGB differed by more than a factor two (i.e more than doubled or halved) in all villages depending on the allometric model (Figure 5). A comparison of the mean estimated AGB in kg of the three villages and the Mount Elgon study sites combined based on the six allometric models showed that Chave (2005), Chave (2014), and Brown produced similar estimates to each other in all four locations (Fig. 5). Comparing these models with Tumwebaze and Segura, a slight trend was identified, that Tumwebaze and Segura produced lower mean AGB estimates than Chave (2005), Chave (2014), and Brown in Bududa and Sipi. This trend was also found when looking at the three villages combined. For the three study sites combined (Mount Elgon) mean AGB estimates ranged from around 265 ± 71.5 kg for the Segura model to 613± 165 kg in for the Brown model.

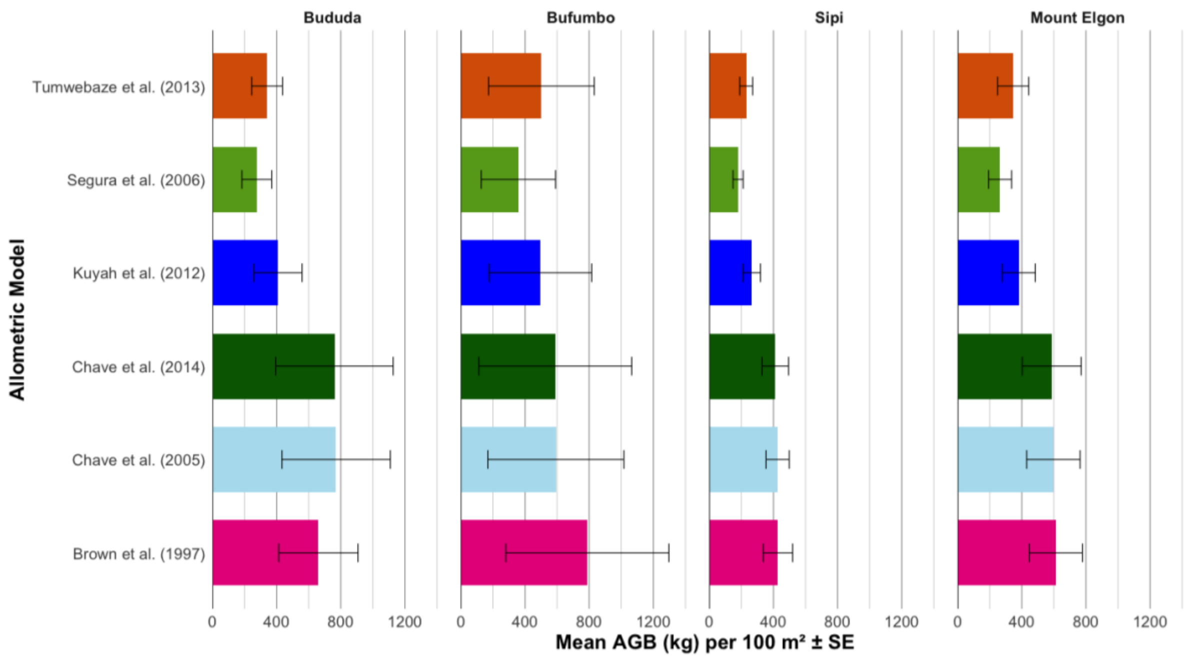

Figure 5: *Mean AGB per 100 m² garden by location for six different allometric models (±SE).*

The summed AGB per 100 m² garden based on an average of the six allometric model estimates ranged from 15-1,956 kg in Bududa, from 3-2,750 kg in Bufumbo, and from 102-590 kg in Sipi before outliers were removed. The mean AGB per 100 m² garden ranged between 226 kg in Bufumbo and 602 kg in Bududa after outliers had been removed, with Sipi showing a mean AGB of 324 kg. A significant difference was found between Bududa and Bufumbo ($p = 0.034$) after log transformation and outlier removal (Fig 6).

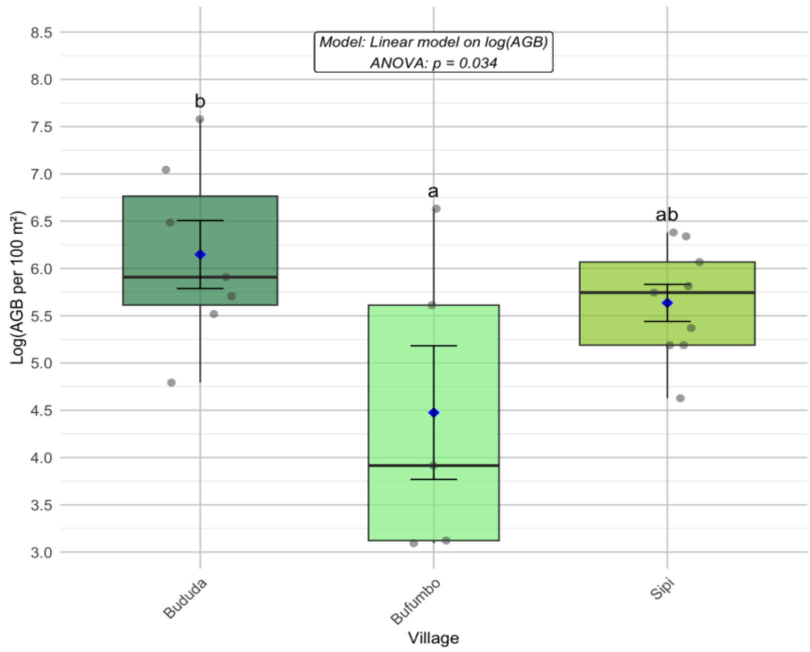

Figure 6: *Summed log-transformed AGB per 100 m² garden by location based on six allometric models with mean (±SE).*

Soil water-stable aggregates

The overall mean WSA content in the soil was 61%. Bududa had a mean total WSA% per garden of 57.5% ± 1.2% (SE) of the total soil mass, which was significantly lower than in Sipi, which had a mean WSA% per garden of 72.6% ±1.8% (SE). This difference was statistically significant (p = 1.08 x 10^{-8}), when comparing just Bududa and Sipi. The effect size ($\eta^2 = 0.57$) indicates that that the village location explains about 57% of the variance in mean WSA% between Bududa and Sipi. Bufumbo had a mean WSA% per garden of 46.9% ± 5.8% (SE) of the total soil mass, but only included three different garden plots.

When looking at aggregate sizes, mean WSA% varied between villages. For the size classes M and S. Sipi had the highest average WSA%, followed by Bududa, and then Bufumbo for both aggregate sizes M and S. For aggregate sizes L and X, no clear trend of WSA% varying between villages was identified. In all three villages WSA% was higher for the size classes L and S than M and XS.

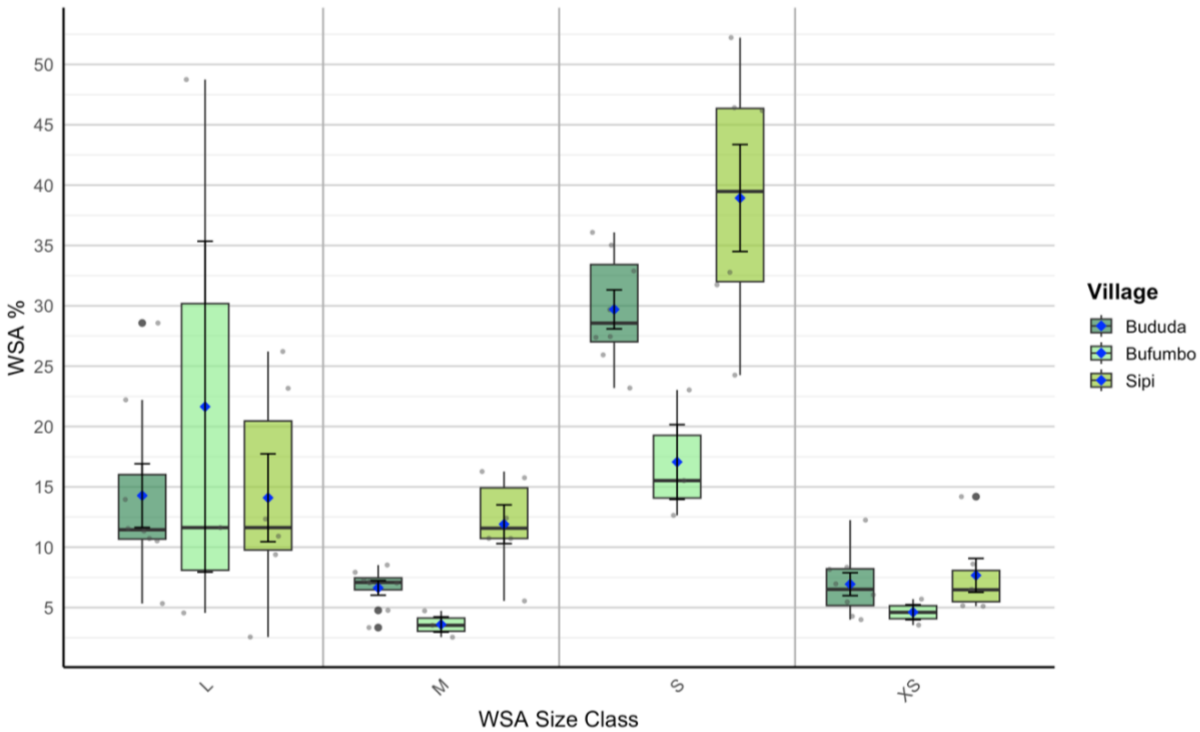

Figure 7: *Mean percentage by mass of WSA in the soil (WSA%) per garden, based on the total mass of the soil samples across WSA size groups, 2000 µm (L), 1000–2000 µm (M), 250–1000 µm (S), and 150–250 µm (XS)for the three study villages with mean (±SE).*

A multiple linear regression analysis found that WSA was mainly influenced by tree density, manure and digging. AGB and weeding by slashing frequency were initially included in the model but were removed during model simplification due to lack of statistical significance ($p > 0.05$). The final reduced model (Eq. 1) was statistically significant (F(3, 46) = 4.89), p = 0.049), explaining approximately 24% of the variance in WSA% (Adjusted R^2 = 0.1924). Tree density had a positive and statistically significant effect on WSA (β = 4.47, p = 0.0027), suggesting that increasing the number of trees per unit area is associated with greater soil aggregation. In contrast, both manure application frequency (β = -1.56, p = 0.0305) and digging frequency (β = -3.42, p = 0.0206) showed significant negative relationships with WSA. This indicates that more frequent manure application and digging are associated with lower soil aggregation levels.

Equation 1:

$$WSA = \beta 0 + \beta 1 \times Tree\ density + \beta 2 \times Manure\ (yearly) + \beta 3 \times digging\ (yearly) + \varepsilon$$

Where WSA are wet-stable aggregates in % of the total mass of soil samples, $\beta 0$ is the intercept, $\beta 1$, $\beta 2$, and $\beta 3$ are regression coefficients and ε is the error term (residuals).

Farmer perceptions on soil erosion and desired tree species

When the 25 informants were asked to describe the erosion levels in their coffee gardens, as they perceived it, roughly 50% of the farmers described the erosion in their garden as moderate and occurring mainly during the rainy season. When comparing the three villages more farmers rated the soil erosion in their garden as mild, and only occurring during the rainy season in Sipi compared to Bududa and Bufumbo, where farmers were more likely to rate the level of erosion in their gardens as severe with occasional erosion occurrences outside of the rainy season (Fig. 8). In addition, only one farmer in Bududa (11.1%) and zero farmers in Bufumbo rated the erosion levels in their gardens as mild.

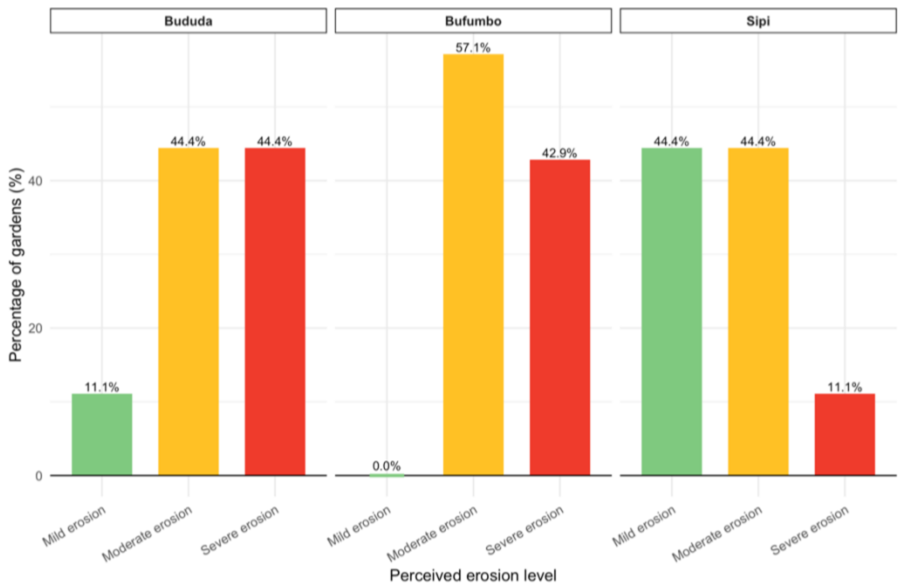

Figure 8: *Percieved soil erosion level among farmers in Bududa (n =9), Bufumbo (n=7), and Sipi (n =9) based on interviews. Farmers ranked erosion risk on a scale from 0 – 2, where 0 = no erosion or mild erosion, only during the rainy season, 1= moderate erosion, mainly during the rainy season, and 2 = severe erosion during the rainy season, and occasional erosion events outside of the rainy season.*

When farmers were asked, if they would like to plant more trees in their coffee gardens considering the trees they already had in their gardens and what species they would like to plant, 23 out of 25 farmers answered that they would like to plant more trees and a total of 14 different trees/ tree species were mentioned (Figure 9a). The most frequently mentioned desired tree species were *Cordia* sp. (56% of farmers) followed by *Persea americana* (28%) and *Albizia* sp. and *Ficus sp.* (20%). Six out of the total of 14 mentioned species were of native origin (N), including the most mentioned (*Cordia* sp.) and third most mentioned (*Albizia* sp.) species (Figure 9a). When asked which farmer benefits or ecosystem services related to the trees the farmers had mentioned, that made them want to plant those specific trees, the answers could be sorted into a total of seven different categories related to farmer benefits or ecosystem services provided by the trees, ranging from contributing to shade, and soil health, to providing income, food, and materials for construction and firewood (figure 9b). The most frequently mentioned perceived benefits from trees was the provision of shade for the coffee plants, mentioned by 72% of farmers, followed by improvements to soil health and stability, and the contribution to generation of income, mentioned by 52% and 44% of farmers respectively.

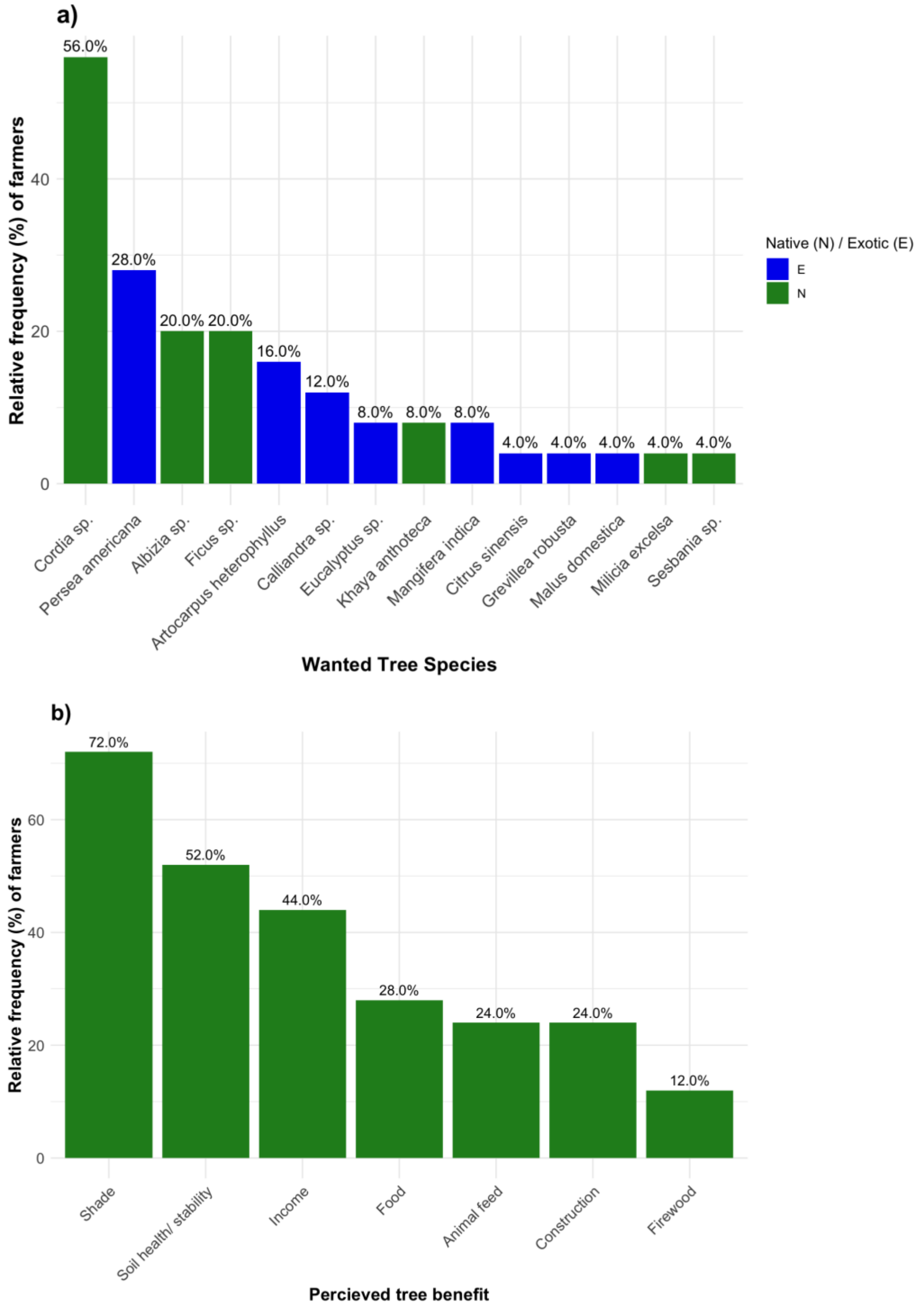

Figure 9: *The frequency (%) of farmers mentioning the* ***a)*** *desired tree species and* ***b)*** *percieved benefits from planting the mentioned trees as a percentage total number of farmers (n=23).*

Discussion

Tree species diversity and composition

Across the three study sites 2 trees were found on average per 100 m^2 garden. Additionally, only 2 unique species were found on average per 400 m^2 garden. This indicates an overall low tree density and species diversity of the coffee agroforestry systems of the Mount Elgon farmers. The low number of identified unique tree species, suggests that the farmers tend to favor a few select species, such as *Eucalyptus globulus, Cordia* sp., and *Persea americana.* This was particularly evident when looking at the native tree species, which were dominated by *Cordia* sp., *Markhamia lutea,* and *Ficus sp. (natalensis)*. Similar findings were reported by Graham et al. (2022), who found that the indigenous species planted in the Kapchorwa and Bulambuli districts were dominated by the species *Cordia africana, Ficus* sp., and *Markhamia lutea*. A potential reason for the low diversity of native trees in the garden plots and low availability of native trees to farmers could be due to loss of native forest at the peripheries of the Mount Elgon National Park due to encroachment into protected areas, which was reported in several studies (Opedes et al., 2022; Sassen et al., 2013; Sebuliba et al., 2023).

Potential reasons for the low number of trees found in the garden plots may be due to increasing pressures on tree planting and existing trees related to the economical and labor costs of tree planting and maintenance, land scarcity, and a strong reliability among local farmers on garden space for subsistence farming in the Mount Elgon region (Opedes et al., 2022; Sassen, 2014; Sassen et al., 2013; Sebuliba et al., 2023). An empirical study conducted by Buyinza et al. (2022) in the Mount Elgon region (Manafwa, Bududa, and Sironko) found that common challenges mentioned by farmers, were concerns about tree-crop competition, overshading due to poor pruning and shade management regimens, and time and labor requirements. Furthermore, a widespread belief was found among farmers, that shade in coffee plantations was related to increased incidence of attack by various pests and diseases. This may indicate a need for more training and knowledge on proper selection of tree species and tree pruning and shade management (Buyinza et al., 2022).

Of all the trees found in the garden plots, 42% on average were native species, and about a third of the 15 most abundant species were native. This indicates a substantial adaptation or incorporation of non-native tree species into the small-scale coffee agroforestry systems found in both Sipi, Bududa, and Bufumbo. A study by Graham et al. (2022) interviewing a total of 161 coffee farmers across 13 villages in the Kapchorwa and Bulambuli districts of the Mount Elgon region also found, that farmers overwhelmingly favored planting exotic tree species over native tree species, limiting the potential benefits of coffee agroforestry systems for biodiversity conservation in the region. This is supported Wagner et al. (2019), who found that farmers on Kilimanjaro in Tanzania often become disincentivized form planting native species due to their slower growth and lack of availability compared to exotic species, although they appreciate the ecosystem services that native species provide, particularly soil fertility enhancement, and shade.

Comparison of allometric models for above ground biomass (AGB) estimation

Overall, the best-fitting models (based on R^2-value), Segura and Tumwebaze were also the lowest estimating models both in terms of AGB per tree and mean summed AGB per village. Estimates of AGB per tree at a $DBH_{1.3m}$ of 50 cm ranged between 900 kg (Segura and Tumwebaze) and 2350 kg (Chave, 2005), and the mean summed AGB per village ranged from around 265 ± 71.5 kg (Segura) to 613± 165 kg (Brown). This indicates that the generalized, pantropical models tended to produce significantly higher AGB estimates than the models that have been adapted to the context of tropical agroforestry systems (e.g. Kuyah, Segura and Tumewbaze), particularly at higher DBH. Several studies have found that application of pantropical generalized allometric equations can cause bias in biomass prediction (Chave et al., 2014; Daba & Soromessa, 2019; Fayolle et al., 2013; Henry et al., 2010; Henry et al., 2011). A study on *Diospyros abyssinica* in Ethiopia found that that the equation by Chave (2005) significantly overestimated AGB at higher DBH classes, which was attributed to a lack of species specific calibration, underscoring the need for localized, species-specific models for more accurate biomass estimation (Daba & Soromessa, 2019). On the other hand, Fayolle et al. (2013) found that pantropical models could produce reasonably accurate estimates of AGB and carbon stock in tropical forests, when incorporating wood specific gravity from global databases was included.

Several studies on allometric models, which highlight the need to adapt allometric models used to estimate AGB and carbon stocks to the specific local conditions, land use type and system, including accounting for variations in species diversity and composition, for more accurate estimates in more system- and region-specific contexts (Chave et al., 2014; Ehrenbergerová et al., 2016; Kuyah et al., 2012; Segura et al., 2006; Tumwebaze et al., 2013). This creates a dilemma, as relatively few allometric equations are reported in Africa compared to other tropical continents (Ngomanda et al., 2014). Tumwebaze et al. (2013) and Segura et al. (2006) emphasized the need for tailored and species-specific biomass equations, due to the variations in tree architecture and growth patterns found in agroforestry systems.

The inclusion of the parameter of tree height by both Chave (2014) and Tumwebaze, suggests that the inaccuracy of tree height measurements may not explain the moderate fit of Chave (2014). The difference found in AGB per 100 m^2 between Bududa and Bufumbo, despite no significant differences in tree density being found when comparing all three villages, suggests that tree density may not adequately explain the variations in AGB found between these villages. Flor-Vélez et al. (2024) found that variations in AGB and carbon storage were associated with differences in species diversity and structural characteristics of agroforestry systems in Ecuador, and that sites with higher tree species diversity had higher carbon storage. Similar findings were reported by Guillemot et al. (2018) for coffee agroforestry systems in in the Western Ghats of India, and by Häger and Avalos (2017) in Costa Rica. Häger (2012) found that farm type, species richness, species composition, and slope explained 83% of the total carbon storage in coffee agroforestry systems in Costa Rica.

Soil water-stable aggregates

The significant difference in percentage of WSA in the soil observed between Bududa and Sipi may be due to differences in soil type between the villages as well as differences in the density of Matoke in the garden plots and the degree of mulching for soil management between the study villages. The density of Matoke and use of banana leaves for mulching was observed to be significantly higher in the garden plots found in Sipi than in Bududa and Bufumbo. The Kapchorwa district, where Sipi is located is dominated by Nitisols, characterized by clay rich, fertile soils derived from organic-rich volcanic parent material (Mugagga et al., 2012a), whereas soil profiles around Bududa and Bufumbo are dominated by Cambisols, Nitisols, Acrisols, and Lixisols with pronounced clay layering and occasional shear planes at depths between 0.2 and 2 meters, contributing to structural instability, especially on steep slopes (Makabayi et al., 2021; Mugagga et al., 2012a).

A trend of variation across different WSA size classes was identified, with the size class S constituting the highest percentage by mass based on the total soil mass. This indicates that most of the WSA in the soil were small aggregates, S. This may be explained by a breakdown of the larger aggregates into smaller aggregates due to erosion and agricultural activities such as weeding by digging, which could be subject for further studies. Several studies have shown a link between deforestation and agri-cultural cultivation practices on Mount Elgon and alterations in the structural and hydrological proper-ties of the soil, which increased the risk of erosion and landslides (Knapen et al., 2006; Mugagga et al., 2012a, 2012b; Oyana et al., 2015). However, a study by Jiang et al. (2014) using the Revised Universal Soil Loss Equation (RUSLE) to estimate soil erosion in the Mount Elgon region for the years 2000, 2006, and 2012 did not find any significant increase in erosion over the examined decade, in spite of the region experiencing increased pressure from agricultural activities and land overexploitation, likely due to improved agricultural management.

In this study, a link between lower aggregate formation and increased digging was found, which was expected as digging breaks down the aggregates in the soil (Knapen et al., 2006; Mugagga et al., 2012a, 2012b; Oyana et al., 2015). Manure application frequency also negatively affected WSA.
A potential explanation for the link between increased manure application and lower aggregate formation might be, that the imbalance and increased activity of microorganisms in the soil resulting from manure application may lead to an increased breakdown of OM in the soil (Lin et al., 2019; Sui et al., 2012; Wen et al., 2021; Wortmann & Shapiro, 2008). On the other hand, increased tree density (as the number of trees per 100 m^2 garden) was associated with higher soil aggregation levels/ WSA

formation in the soil. This may be related to the higher levels of soil organic carbon (SOC) in soils with more trees (Lugo-Pérez et al., 2023; Nandini et al., 2022; Ortiz-Ceballos et al., 2020; Panwar et al., 2022; Tschora & Cherubini, 2020). Several studies found that tree roots stabilize slopes and improves soil health by reducing runoff and promoting aggregate formation (Claessens et al., 2007; Gram et al., 2018; Knapen et al., 2006; Wagner et al., 2019)

AGB and weeding by slashing were not found to have any significant effect on soil WSA%. This may be explained by the fact that AGB alone does not necessarily reflect below-ground biological processes, such as root biomass and microbial activity, which are more directly involved in soil aggregation. Similarly, slashing does not mechanically disrupt the soil, but the limited contribution in terms of organic residue, may not significantly influence aggregate formation. Other studies found that sustainable land use practices, involving minimal disturbance to the soil and permanent vegetation cover, may be more influential in promoting stable soil aggregates than biomass quantity alone (Mugagga et al., 2012b; Oyana et al., 2015; Sassen et al., 2013; Sebuliba et al., 2022).

Farmer perceptions on erosion levels and desired tree species

The differences in farmer perceptions on erosion levels cannot be attributed to differences in average slope or tree density between the villages. During interviews, it was observed, that farmers in Sipi had higher densities of Matoke, which is not considered a shade tree, but is a shade plant and was also used for mulching. This may partly explain why farmers in Sipi seemed to rate the erosion in their coffee gardens as less severe. Differences in soil type between the villages may also explain the differences in perceptions on erosion levels between farmers in the three villages. The more stable soils found in Sipi compared to Bududa and Bufumbo may explain why farmers in Sipi are the least likely to rate the erosion levels in their coffee gardens as severe (Makabayi et al., 2021; Mugagga et al., 2012a). However, further studies are needed to investigate the influence of different garden specific factors on farmer perceptions on the severity of erosion.

Cordia sp., *Persea americana,* and *Albizia* sp. were the most frequently requested trees by the farmers (23 informants). Of these species *Cordia* sp. (*C. africana* or *C. millenii*) and *Albizia* sp. are native. I total 7 out of 15 of the mentioned species were native. This indicates that a substantial amount of the wanted tree species are exotic, which aligns with preference for exotic species found when looking at the relative percentage of exotic species found in the coffee gardens of the same farmers.

The most mentioned tree benefits or ecosystem services by the farmers were shade, improvements to soil health and stability, and contribution to the household's income. The ability to directly provide food, animal feed, and construction material were also highly mentioned benefits (mentioned by roughly ¼ of farmers). Trees that provided food or construction materials (timber) were often also used to generate income, explaining why income was frequently mentioned by farmers. Wagner et al.

(2019) found that he most highly ranked out of a series of ecosystem service/ benefits from trees among farmers in Tanzania who engaged in coffee agroforestry practices were food provision, firewood supply, and animal feed provision, which were also significant benefits mentioned by the farmers on Mount Elgon. Additionally, shade and various soil fertility benefits were also highly ranked by farmers in Tanzania, similar to the findings of this study (Wagner et al., 2019). Gram et al. (2018) also found that farmers at higher altitudes on Mount Elgon prioritized ecosystem services related to soil fertility and erosion control higher than services such as microclimate regulation and coffee yields.

Conclusion

This study offers insight into the tree species diversity and composition, above-ground biomass stock, soil structure and stability, and farmer perspectives in smallholder coffee agroforestry systems on Mount Elgon. The overall low tree density and species richness, coupled with the dominance of a few exotic species, suggest that current agroforestry practices are shaped by a combination of practical constraints and common species preferences among farmers. However, the high proportion of farmers expressing a desire to plant more trees, especially native trees such as *Cordia sp.* and *Albizia* sp., indicates a strong potential for promoting more diverse and multifunc-tional agroforestry systems. The comparison of allometric models revealed significant variation in AGB estimates, with allometric models developed for the context of tropical agroforestry systems (e.g., Tumebaze and Segura) offering higher predictive performance than generalized pantropical models (e.g. Chave and Brown). This highlights the importance of using context-specific models for more accurate carbon stock estimation in agroforestry systems. In terms of soil stability and WSA formation, tree density was positively associated with WSA formation, whereas more frequent digging and manure application were linked to lower aggregate stability, suggesting that certain management practices may undermine soil structural stability. Altogether, the results point to a potential for improving ecosystem services and resilience and soil health and stability through an increased and more deliberate integration of trees into coffee growing systems. Providing farmers with support for selecting appropriate species, could enhance tree density, diversity, AGB formation and carbon sequestration as well as WSA formation, leading to more productive systems and less soil erosion.

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13. Appendix

Appendix 1: *Names of identified species translated into Kupsabiny, Lugishu, and Luganda*

Species, Latin name	Author name	English name	Lugishu name	Kupsabiny name	Luganda name	Native (N)/ Exotic (E)
Acrocarpus fraxinifolius	Wight & Arn.	Shingle tree/ Pink cedar	-	-	-	E
Albizia coriaria	Welw. ex Oliv.	Albizia	Guluku	Mutahnwet	Mugavu	N
Artocarpus heterophyllus	Lam.	Jackfruit	Fenne/ Kifanensi	Fenne	Kifenensi/ Yakobo	E
Azadirachta indica	A. Juss	Neme tree	Albaine	-	Neme	E
Carica papaya	L.	Papaya	Paw Paw	Paw paw	Papaali	E
Casimiroa edulis	La Llave	White sapote	Shikunda/ Shicangu	Kamelionwet	-	E
Cerbera manghas	L.	Sea mango	-	Meniambtet	-	E
Cordia africana	Lam.	Sudan teak	Kukyihili/ Chichikiri	Mukekenret	Mukebu	N
Cordia millenii	Baker	Drum tree	Kukyihili/ Chichikiri	Mukekenret	Mukebu	N
Cordia sp.	L.	Cordia	Kukyihili/ Chichikiri	Mukekenret	Mukebu	N
Croton macrostachyus	Holchst. ex Delile	Broad leaved croton	Luiyi/ Guiyi	-	Musogasoga	N
Cupressus lusitanica	Mill.	Mexican cypress	Cypress	Cypress	-	E
Eucalyptus camaldulensis	Dehnh.	Murray red gum	Ekaliputusi	Buliayet	Kalitunsi	E
Eucalyptus globulus	Labill.	Tasmanian blue gum	Ekaliputusi	Buliayet	Kalitunsi	E
Eucalyptus grandis	W.Hill ex Maiden	Rose/ red/ flooded gum	Ekaliputusi	Buliayet	Kalitunsi	E
Ficus bigusa	-	Bigusa fig	Kumutongu	-	Figa	N
Ficus natalensis	Hochst.	Natal fig	Gukaire	Smotret	Mutuba	N
Ficus thonningii	Blume	Strangler fig/ Common wild fig	Gutoto/ Kutoto	-	Figa	N
Ficus sp. (thonningii)	-	Ficus (Strangler fig/ Common wild fig)	Kuwuyu/Gukuyu	-	Figa	N
Grevillea robusta	A.Cunn. ex R.Br.	Silk oak / Silver oak	Lusubyui/ Kusubyu	Kowoiyet	-	E
Khaya anthotheca	(Welw.) C.DC.	East african mahogony	Gumutumba	-	-	N
Leucaena leucocephala	(Lam.) de Wit	(Pink) Leucaena/ Leadtree	-	-	Ekikankanyi	E
Maesopsis eminii	Engl.	Umbrella tree	Musizi	-	Musizi	N
Mangifera indica	L.	Mango tree	Muyembe	Muyembiontet	Muyembe	E
Markhamia lutea	(Benth.) K.Schum.	Nile tulip	Kusora/Lusola	Swayet	Nsambya/ Lusambya	N
Milicia excelsa	(Welw.) C.C.Berg	Rock elm/ Iroko	Movule	-	Movule	N
Persea americana	Mill.	Avocado tree	Ovacado/ Ovokedo	Ovocado/ Ovokedo	Ovokedo	E
Pinus patula	Schiede ex Schltdl. & Cham.	Patula pine	-	-	-	E
Psidium guajava	L.	Guava	Mapera	Mapera	Mupeera	E
Ricinus communis	L.	Castor oil plant	Gubonu	Manuiwet	Nsogasoga	E
Warburgia ugandensis	Sprague	East african greenheart	Nabutidi	-	Mukuzanume/ Muwiya	N

Appendix 2: *Summary of abundance and frequency of the identified tree species*

Latin name	Native(N)/ Exotic(E)	Total count	% of garden plots	% of total trees
Eucalyptus globulus	E	112	36	27.2
Cordia sp.	N	72	64	17.5
Persea americana	E	27	52	6.6
Markhamia lutea	N	26	28	6.3
Eucalyptus grandis	E	22	20	5.3
Eucalyptus camaldulensis	E	18	12	4.4
Grevillea robusta	E	18	28	4.4
Artocarpus heterophyllus	E	14	20	3.4
Mangifera indica	E	12	28	2.9
Ricinus communis	E	12	12	2.9
Ficus natalensis	N	11	20	2.7
Croton macrostachyus	N	9	24	2.2
Pinus patula	E	8	4	1.9
Acrocarpus fraxinifolius	E	7	8	1.7
Maesopsis eminii	N	7	4	1.7
Albizia coriaria	N	4	12	1.0
Casimiroa edulis	E	4	8	1.0
Cerbera manghas	E	4	8	1.0
Milicia excelsa	N	4	8	1.0
Ficus thonningii	N	3	8	0.7
Warburgia ugandensis	N	3	8	0.7
sp1	-	2	8	0.5
Azadirachta indica	E	2	4	0.5
Cupressus lusitanica	E	2	8	0.5
Ficus sp. (thonningii)	N	2	4	0.5
Leucaena leucocephala	E	2	4	0.5
Psidium guajava	E	2	4	0.5
Carica papaya	E	1	4	0.2
Ficus bigusa	N	1	4	0.2
Khaya anthotheca	N	1	4	0.2

Appendix 3: *Combined questionnaire with interview questions*

Date:

1. **Identification**

Garden-ID, (Village)	
Name of owner	
Age of owner	
Gender of owner	
Total garden size (acres?)	
Size of land used for coffee/AFS	
Location coordinates	A. B. C. D.
Facilitators	
Translator(s)	
Recording no.	

2. **Management practices**

1. Are there other people working in the gardens?

2. What types of arabica coffee do you grow in this garden?

3. When was the coffee established in this garden?

4. Are some of the coffee plants in this garden established at different times?

5. What was grown in the garden before this AFS/ coffee garden was established?

6. How often do you stump the coffee?

7. How often do you apply manure?

8. What types of manure do you use?

9. How often and when do you remove weeds by digging?

10. How often and when do you remove weeds by slashing?

3. **Open-ended questions:** Farmer perceptions

11. Is the soil erosion severe in your garden?

12. When and how often do you experience erosion?

13. What are the main reasons you plant trees in your garden?

14. What are the barriers to planting trees in your garden?

15. What trees would you like to have more of in your garden and why?