



Building a climate resilient Robusta coffee agroforestry system in Uganda: a research perspective

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Abstract Climate change may impose severe challenges to coffee farmers to maintain agricultural production levels especially in smallholder farmers, who produce 90% Uganda's coffee. In Uganda, Robusta coffee, which accounts for 80% of the total coffee production is predicted to be significantly affected. Climate adaptation and mitigation measures are required to moderate some of the worst predicted scenarios. Agroforestry has been highlighted as a cost-effective and sustainable strategy for modulating the effects of climate change in coffee farms given its contribution to carbon sequestration, reducing greenhouse gas emissions, diversification of tree and forest products, and reduction in the susceptibility of land-use systems to extreme weather events, among others. However, various research gaps need

to be addressed, for deriving optimal benefits from agroforestry for climate change adaptation and mitigation in coffee. Paradoxically, while nearly all Robusta coffee is historically conducted using agroforestry methods, the growing negative view of the role of trees, especially the possibility of shade tree species serving as a reservoir for pests calls for concerted research efforts to guide the promotion of agroforestry methods to curb the development of monocultures. The review, therefore, highlights; (i) current knowledge relating to agroforestry tree choice, (ii) knowledge on above/below-ground interactions between trees and Robusta coffee from plot to landscape scales, and (iii) research areas that need to be addressed for building climate resilient Robusta coffee agroforestry (CAF) systems. Selecting appropriate agroforestry tree species and managing above and below-ground resources appear to be key factors for optimizing Robusta coffee production, but most of the information is missing in the context of Uganda's Robusta coffee-agroforestry systems. In the face of climate change that is likely to affect the biophysical environments and social structures, approaching the research activities through living laboratories, to collaboratively co-create, develop, and test new technologies, products and services in real-life environments could yield more practical solutions.

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Background

Current climate change models predict temperature increases anywhere from 2 to 5 °C over the next 75 years (Stern 2008), but next-generation models predicted that “equilibrium climate sensitivity” might come in at 5 °C or warmer. These changes in climate are already imposing severe challenges to farmers to maintain sufficient agricultural production levels (Karki et al. 2020). In developing countries, it is now evident that the consequences of climate change are causing great harm to agriculture (Hassan and Nhemachena 2008; Mendelsohn 2009; Stigter and Ofori 2014). This is particularly the case for producers of coffee, which is an important cash crop for approximately 25 million smallholder farmers and 100 million livelihoods in many countries in Africa, Mesoamerica, and South America (Gomes et al. 2020b). An analysis by the Stockholm Environment Institute (Adams et al. 2021) suggests that climate change could reduce global Arabica and Robusta by 45.2% and 23.5% respectively. Although quantifying and understanding these impacts provides important insights into how much to spend on mitigation or help direct where, when, and how adaptation should proceed, climate adaptation and mitigation measures are promptly required to moderate some of the worst predicted scenarios.

In Uganda, coffee is a major cash crop, accounting for 20–30% of foreign exchange earnings, and is key to smallholder livelihoods (Parizat et al. 2011; You and Bolwig 2003). About 1.7 million smallholder farmers (10% of global farms) whose average farm sizes range from 0.5 to 2.5 ha produce 90% of Uganda’s coffee (Jassogne et al. 2013; UCDA 2019). The total area under coffee production in Uganda can be estimated at 353,907 ha (Mugoya 2018). Four indigenous varieties of coffee are known in Uganda (Davis and Kiwuka 2023), but Robusta (*Coffea canephora* Pierre ex Froehn.) and non-indigenous Arabica (*Coffea arabica* L.) are the two species mainly grown. Robusta is predominant at lower elevations (< 1400 m) such as in central and northern Uganda, and Arabica is dominant at higher elevations (> 1400 m) in the eastern, southwest, and northwest Uganda (Van Asten et al. 2012). Robusta and Arabica are estimated to comprise 80% and 20% of the total production in Uganda, respectively (Van Asten et al. 2012), where Uganda accounts for 7% of global

Robusta exports (www.ugandacoffee.go.ug, accessed in August 2022). However, the quantity and quality of coffee, and hence incomes, have been projected to be constrained by changing temperature, precipitation regimes, pests and diseases (Kath et al. 2021), as well as the shrinkage of the suitable land area under coffee (Jassogne et al. 2013) resulting from climate change. Predictive studies by (Abigaba et al. 2024; Bunn et al. 2015) for instance, show that climate change will reduce the area suitable to grow Robusta and Arabica coffee by respectively, 9% and 20% by 2050. Currently, in Arabica growing areas in Uganda, prolonged droughts, erratic and shorter rains have been associated with flower abortion, poor filling and increased pests and diseases (Davis et al. 2012; Dekens and Bagamba 2014; Jassogne et al. 2013). Additionally, climate hazards reduce coffee yield and quality through: physiological disruptions of the coffee trees; the deterioration of coffee seedlings; the disruption of the bean-drying process; and the destruction of inputs and infrastructure for processing and transportation (Dekens and Bagamba 2014). Decreasing coffee quality affects coffee prices and the margins earned by the various actors, which impacts the country’s competitiveness on the international market (Dekens and Bagamba 2014).

While Robusta is generally more tolerant to harsh weather and pests and diseases compared to Arabica, studies show that it is susceptible to high temperatures i.e., above 30 °C especially during critical phenological stages (Kath et al. 2020). Since the impacts of climate change will be more significant at low altitudes (Bunn et al. 2015; Wang et al. (2015), this suggests that in Uganda, Robusta coffee growing will potentially be more affected than Arabica, contrary to Adams et al. (2021) global prediction. Therefore, strategies to minimize production risks of Robusta should be considered in farming systems. Currently, environmental, technological, economic, financial or organizational risk-management strategies such as, development of coffee cultivars adapted to the climatic changes, and agronomic solutions such as targeted irrigation during hot and dry growing seasons, adjusting harvest timing and employing drying techniques during wet and cold harvest periods, that can minimise the effect of climate conditions on coffee production have been recommended (Dekens and Bagamba 2014). These, however, may not be affordable by many smallholder

farmers who are the largest producers in Uganda. Agroforestry management systems are envisaged as a promising sustainable low-cost and green approach to mitigate and adapt coffee production to climate change and variability (Gomes et al. 2020b; Lin 2007; Tumwebaze and Byakagaba 2016; Wang et al. 2015) including the associated pests and diseases. According to FAO, agroforestry induces a significant increase in productivity better than any other innovation introduced by agronomists in the recent past (FAO 2017).

Agroforestry, which covers around 43% of agricultural lands globally (Zomer et al. 2014) is not a new concept in Uganda. Historically, Ugandan farmers have always integrated useful trees and shrubs on farms, and consequently nearly all robusta production occurs within agroforestry systems. Literature shows that research and development organisations in Uganda continue to make considerable efforts in promoting and disseminating agroforestry technologies in different parts of the country for various environmental and socio-economic benefits (Bukomeko et al. 2018; Fungo et al. 2020; Gwali et al. 2015; Kagezi et al. 2018; Kiyangi and Gwali 2012; Okorio et al. 2004; Tumwebaze and Byakagaba 2016). In central Uganda, where more than 77% of Robusta is produced (<https://alliancebioiversityciat.org/stories/climate-smart-coffee-uganda>, accessed October 2024), simultaneous coffee-agroforestry (CAF) systems are predominant, as is for most perennial crop systems. The general view is that trees in coffee provide diverse benefits such as additional food and incomes, improving the microclimate, increasing ecosystem biodiversity and health, soil nutrient availability, carbon sequestration as well as reducing pest and disease damage among others (Abd El-Zaher 2008; Fungo et al. 2020; Kyarikunda et al. 2017; Zake et al. 2015). However, contradicting views on the contribution of agroforestry to productivity have been documented, affecting the success of agroforestry (Durand-Bessart et al. 2020; Piato et al. 2020). Currently in Uganda, tendencies towards monocultures are observed as a result of farmers' changing views on the risk of maintaining trees that are apparently a reservoir of pests. Such views have been documented in other countries, for instance, introduction of *Grevillea robusta* in Robusta CAFs of India negatively affected ecosystem services such as carbon storage (Guillemot

et al. 2018). Moreover, leguminous shade trees did not make a significant contribution to Robusta coffee yields in the Ecuadorian Amazon (Chavez et al. 2021). A worst-case scenario would be for Uganda to implement the practices adopted by the two largest robusta producers, Vietnam and Brazil, which primarily rely on full-sun production for robusta coffee (ICCO 2014). Souza et al. (2010) emphasized that the potential of coffee shade tree integration can only be realized when appropriate shade tree species are selected and well managed to get appropriate above and below-ground conditions such as crown shape, shade production, foliage density, root system attributes, and allelopathic effects. Therefore, a proper CAF strategy based on proper tree choice and management, spatial assembly of tree/shrub layers, and soil characteristics (Durand-Bessart et al. 2020; Gram et al. 2018; Piato et al. 2020; Souza et al. 2010) is crucial. This review aimed to explore the research gaps that need to be addressed for optimal contribution of agroforestry systems to mitigate the impacts of climate change on Robusta coffee in Uganda. Our analysis will be based on;

- (i) current knowledge relating to tree choice for Robusta coffee agroforestry
- (ii) knowledge on above- and below-ground interactions between trees and Robusta coffee at plot to landscape levels in Robusta coffee-agroforestry systems.
- (iii) examples of research areas that need to be addressed for building climate resilient Robusta coffee agroforestry systems in Uganda.

Tree species choice in Robusta coffee-agroforestry

The composition and density of tree species in Robusta coffee-based agroforestry systems (CAFs) varies across the country (Figs. 1 and 2). Coffee-banana-trees intercropping systems (Fig. 1) are the most predominant traditional farm management systems especially in the south-western, central and eastern Uganda, where an estimated 75% of farmers intercrop coffee and banana on at least part of their coffee farm (Bongers et al. 2012; Oduol and Aluma 1990). While the benefits of banana intercropping on coffee production have been reported (Van Asten



Fig. 1 Simultaneous coffee-banana-trees intercropping systems

et al. 2011), evidence for the effect of tree species is more scarce, probably due to the diversity of tree species on different farms, and limited research. In central Uganda, the predominance of *Ficus natalensis* Hochst., *Albizia coriaria* Welw. ex Oliv., *Artocarpus heterophyllus* Lam., *Maesopsis eminii* Engl., *Mangifera indica* L., *Cordia africana* Lam. and *Persea americana* Mill. is observed on coffee farms (Gwali et al. 2015; Isabirye et al. 2008; Kalanzi 2015). In eastern Uganda (Bugisu region), the main tree species in Robusta coffee systems are *C. africana*, *Albizia gummifera* (J.F.Gmel.) C.A.Sm., *A. heterophyllus*, *Markhamia lutea* (Benth.) K.Schum., *P. americana*, *Croton macrostachyus* Hochst. ex Delile, *M. indica* and *Cordia millenii* Baker (Negawo and Beyene 2017; Okorio et al. 2004). In mid-northern Uganda, fruit trees such as *Citrus spp*, *M. indica* and *Carica papaya*, and indigenous species such as *Ficus spp*, *Combretum collinum* Fresen., and *Lonchocarpus laxiflorus* Rolfe are also integrated in

CAF systems, but in less than 50% of the coffee farms (Kagezi et al. 2018).

In Uganda, farmers either plant trees or maintain them by natural regeneration (Gwali et al. 2015; Isabirye et al. 2008; Negawo and Beyene 2017), but the choice of tree species is informed, besides cultural norms, by the different benefits that they provide which are mainly categorised as: provisioning services (food, firewood, timber, medicine, poles etc.), and/or regulatory services (shade, soil productivity, pest and disease control, carbon sequestration and climate amelioration) (Bukomeko et al. 2019; Gram et al. 2018; Kagezi et al. 2018; Kagezi et al. 2013; Negawo and Beyene 2017; Tumwebaze and Byakagaba 2016). Similar drivers have been documented in other Robusta growing countries, for instance in Brazil (Zaro et al. 2019), Rwanda (Smith Dumont et al. 2019), Tanzania (Wagner et al. 2019), and Vietnam (Nguyen et al. 2020; Van et al. 2018). In Southwestern Amazon region of Brazil (Rondônia), the development of Robusta CAF is mostly based on intercropping with Brazil nut and Teak (de Oliveira Bezerra et al. 2024), whereas Rubber trees are used in Southern Brazil (Zaro et al. 2019). In the Northwest Vietnam, leguminous trees like *Leucaena leucocephala* are integrated in CAF systems as support for pepper trees but also for their benefit in soil nutrient improvement and provision of shade, which are crucial for sustainable coffee production (Nguyen et al. 2020). Recent investigations in the Central Highlands Vietnam estimated that approximately half of coffee farmers manage diversified plots, notably with pepper and fruit trees (Clément et al. 2023).



Fig. 2 Coffee-agroforestry system showing **a** non-shaded and **b** dense agroforestry trees

A wide range of tree attributes such as shade quality, leaf litter quantity and quality, growth rate and root architecture are also used to select agroforestry tree species and infer the services that are likely to be provided by different tree species (Bukomeko et al. 2018; Cerdán et al. 2012; Kalanzi 2015; Sebuliba et al. 2022; Valencia et al. 2015). Socio-economic factors have been documented as influencing the adoption of agroforestry in coffee systems, notably tree tenure security, seed supply, size of landholding, contact with extension and research agencies and farmer gender (Kyarikunda et al. 2017; Oduol and Aluma 1990; Okorio et al. 2004; Okullo et al. 2003). Related factors have been documented in studies outside Uganda. For instance, age, farming experience, education level, and land size affected choice of tree species by farmers in Kwazulu Natal in South Africa (Zaca et al. 2023); food, fodder and fuelwood in Tanzania (Wagner et al. 2019).

Recently, scientists and extension workers have also influenced the choice of trees by promoting trees which have positive attributes such as high carbon-sequestration potential, pest and disease regulation, diversified incomes and biodiversity conservation (Bolwig et al. 2006; Cerda et al. 2020; Hulme et al. 2013; Kiyangi and Gwali 2012; Piató et al. 2020; Tumwebaze and Byakagaba 2016). CAF tree choice may be also be partly influenced by the native indigenous species that dominate the different agroecological zones.

In selection of trees, some farmers are also aware of the disincentives such as tree species that are prone to tree falls and trees whose leaves do not easily decompose (Bukomeko et al. 2018; Kalanzi and Nansereko 2014; Sebuliba et al. 2022). Shade is also still a highly contentious factor for coffee production in terms of potential yield reduction, as well as additional management needs and interactions between shade trees and pest and disease (Koutouleas et al. 2022). While trees contribute to regulation of pests and diseases in coffee systems (Nesper et al. 2017; Piató et al. 2020), studies also indicate that they can facilitate the high incidences of the same (Bukomeko et al. 2018). It has also been noted that the choice of trees is informed by tradeoffs in the benefits and disincentives provided by the different potential tree species (Sebuliba et al. 2021).

Climate change may potentially affect agroforestry tree behavior and choice, and hence the need for

concerted efforts in determining the dynamic relationship between climate change, trees and coffee. Studies have indicated that climate change could disrupt local adaptation, resulting in maladaptation and possibly extirpation of trees (Gougherty et al. 2021), which can have implications of tree choice and suitability in CAF. Drought can, for instance, reduce tree growth, increase the vulnerability of trees to insects and diseases, and drive tree mortality, which may reduce suitability of the traditional agroforestry tree species. This could potentially explain the growing rejection of traditional CAF trees in Uganda such as *F. natalensis* that has recently been cited as a host for the coffee twig borer.

Therefore, research areas in view of tree choice in Robusta-coffee agroforestry could include:

- i. Selecting the most appropriate agroforestry trees based on scientific evidence of the interactions. This may involve for example, modelling the effects of leaf phenology or root structure etc. on growth, nutrient and water use, and light interception of key CAF trees on coffee as demonstrated in other studies (Muthuri et al. 2004). Such studies can elucidate any potential complementarity and trade-offs. Moreover, the contribution of some tree species in CAFs to ecosystem services such as biodiversity conservation or carbon sequestration needs to be further evidenced.
- ii. Understanding the use of knowledge by farmers to adopt agroforestry, select and manage or reject coffee agroforestry trees should be useful in promoting agroforestry in Robusta growing areas. However, this local knowledge should be complemented with scientific knowledge, especially given that the ongoing changes in climate are likely to challenge local knowledge, for example through affecting habitat suitability, physiology and phenology of tree species (McMillan 2023). Gender considerations are very important in this case as men and women interact with the trees and coffee differently and can harbor distinct knowledge (Galabuzi et al. 2021).
- iii. Understanding the perception of farmers towards adoption of tree management practices in coffee systems. Understanding farmers' perceptions on CAF and tree management

can help support their efforts and develop interventions more suited to the local context. For example, shade management in coffee has received limited appreciation by farmers. Instead it is done to fulfill other needs, e.g., farmers in eastern Uganda mainly pruned their trees to get firewood and not necessarily to maintain the appropriate shade on their coffee farms (Buyinza et al. 2022). The perception of both women and men needs to be taken into consideration given the different roles they play on farms (Galabuzi et al. 2021).

- iv. Exploring new or currently ‘unknown’ or ‘unused’ or ‘non-traditional’ potential coffee-agroforestry trees selected based on phenotypic traits such as root and crown shape, allelopathy properties or leaf phenology. There may be need to diversify the trees to non-traditional species since known ones could become unsuitable in the face of extreme weather conditions (such as tree falls reported in vegetatively propagated *Ficus natalensis* trees).
- v. Designing CAF planting modes for optimal productivity and accurately predicting productivity of different tree-crop mixtures. The inclusion of trees in coffee crops should reconcile social, ecological and economic goals. However, progress in promoting agroforestry is held back because decision-makers lack reliable tools to accurately predict yields and hence profitability from designs, due to the complexity of different plant combinations especially for smallholder farmers. Several agroforestry models and model families have been developed, including SCUAF, HyPAR, Hi-SAFE/Yield-SAFE and WaNuLCAS (Mahato and Kadaverugu 2024), but these haven’t been adapted to Robusta coffee.
- vi. Breeding trees with desirable ecological traits. Management strategies for reducing below and above ground challenges for CAF have been recommended by several studies. To reduce aboveground competition, practices include; tree spacing, pruning to manage branch density or shade and selecting trees with less compact crowns or those which do not attract pests and diseases. To minimize below ground antagonism, the recommendation is to select trees with deeper rooting system. Attempts to

manage above ground competition are common but root management in AF is quite complicated and rarely undertaken. Either case, management to achieve the desirable level of traits can be complex, costly and time consuming and not frequently done by smallholder farmers. This sets an important research agenda, where genetic improvement of important traits for AF is a goal worth pursuing. Phenotypic variation among populations for some key functional traits such as such as rooting depth, crown densities, water-use strategy, foliage longevity, chemical defences, microbial interactions, insecticidal properties, leaf and flower phenology have been observed in various plants including trees (Nantongo et al. 2025, 2022, 2021; Tortosa et al. 2016) that could be a basis for selection. If this variation has a significant genetic component, then it can be subject to breeding and improvement. Moreover, selecting genetically appropriate tree populations for quality germplasm can enhance adaptation of trees to climate change. Techniques for genetic characterization of natural tree populations are well established (Nantongo et al. 2016, 2022a, 2023).

Tree-crop interactions

Properly delineating appropriate agroforestry trees to develop climate resilient Robusta agroforestry systems, should be examined in view of both the above and below-ground interactions (complementarity and competition). It is well known that tree * management * crop interactions can create a continuum of above and below-ground interactions in agroforestry systems, with the net effects of interspecific species interactions varying in both sign (–, 0, +) and magnitude (strong to weak). The positive interactions show complementarity, while the negative interactions show competition. Normally positive interactions manifest as improved soil and plant productivity, nutrient cycling, soil fertility and biodiversity (Wright et al. 2024) while the negative effects such as competition manifest as reduced productivity and ecosystem services of the system.

Above-ground interactions

Above-ground interactions in agroforestry systems involve competition for light, temperature, and humidity. Trees often have larger and more extensive canopies compared to coffee, which can result in shading and reduced light availability, potentially impacting photosynthesis and coffee yields. The effects of above-ground interactions on Robusta tree growth and yield such as shade and its interactive effects in CAF have received fair coverage as highlighted in the meta-analysis by Piato et al. (2020) and research studies in key robusta producing countries like Brazil (Araújo et al. 2016) and Vietnam (Le et al. 2023; Van Long et al. 2015). These publications indicate that agroforestry trees can decrease the maximum daily air temperature by up to 4 °C in Robusta coffee, reduce variation of minimum and maximum temperature, and soil and water loss (de Carvalho et al. 2021; Merle et al. 2022). Consequently, unshaded coffee systems have shown strong yearly fluctuations in flowering, which results in a biennial production pattern with alternating years with high and low productivity (DaMatta 2004). These fluctuations decrease the lifespan of coffee plants due to exhaustion during heavy production years (DaMatta 2004). On contrast, poorly managed shade may negatively influence the physicochemical and biochemical properties of coffee (Piato et al. 2020). Increasing shade, for example, can affect the physiology of coffee plants, stimulating the vegetative growth instead of flower buds, reducing the number of nodes per branch and coffee yield (Bote and Struik 2011). Excessive shade can also exacerbate pest and disease problems (Bukomeko et al. 2018; Kagezi et al. 2013). Therefore, the management of above-ground part of agroforestry systems to deal with light availability, temperature, and humidity, and biotic factors should be of ultimate concern.

In Uganda Robusta farms, for example, increasing shade from 0–20% to 41–60% shade can potentially increase of infestation by the black coffee twig borer. Interestingly, high shading is important to reduce evapotranspiration, for example, with 60–80% shade cover, daily soil evaporation rates significantly decreased by 41% in Mexican Robusta coffee-agroforestry systems (Lin 2010). Increasing relative humidity can favour growth and the development of soil microorganisms (Piato et al.

2020; Tumwebaze and Byakagaba 2016), which call s for proper examination of such tradeoffs. However, the extent and impact of shade depends on tree species characteristics, canopy structure, and spatial arrangement (Muñoz-Villers et al. 2020) as well as the associated crop traits such as coffee variety and age (Piato et al. 2020). For instance, intercropping a fast-growing tree species in coffee might stifle the growth of the crop because they all demand a significant amount of light in their early stages. Although careful design of the spatial configuration and/or management practices, such as tree pruning are often used to maintain the shade at an appropriate level and ensure a balance between productivity and ecological benefits (Jose 2009), mechanisms for managing above-ground interactions in CAFs are context specific and should be explored further in order to maximise the benefits and minimise the costs of tree-crop interactions. Therefore how much shade is enough to give optimal results, is still of interest.

As such we highlight the following research areas:

- i. Determining appropriate silviculture practices for traditional agroforestry trees. Optimal benefits of tree-crop interactions on coffee-agroforestry farms can be realised if farmers adopt the appropriate silviculture and tree management practises. While there is some information on the trees adopted by farmers and the factors influencing the adoption, there is a dearth of studies on adoption of silviculture and tree management practices by farmers. A study by Buyinza et al. (2023), for example showed that persistent canopy pruning reduced water demand for the tree component and allowed recharge in the crop rooting zone, which would especially be beneficial in the dry season.
- ii. Examining optimal tree-coffee shade effects with recognition that the radiation transmitted under trees is neither uniform in time and space, nor of the same spectral composition as the incident radiation above the trees.
- iii. Determining the number of trees that are adequate in coffee-agroforestry systems per given land size. In Robusta growing areas of central and western Uganda, where more than 77% of Robusta is produced it is indicated that a large share of coffee farmers do not have adequate shade trees on their coffee farms

(Bongers et al. 2012). But how many trees are sufficient in a coffee farm is still debatable. A discussion on research gate suggests that up to 40–50 trees per hectare (or trees forming at least 20% of tree crown cover) can form an agroforestry system (<https://www.researchgate.net/post/What-should-be-the-minimum-tree-density-in-traditional-agroforestry-systems>). It is also indicated that the number of trees could be influenced by the tree species and species*crop combinations, tree management, socio-economic status of the families among others. A guide for determining the number of trees per land size needs to be developed.

- iv. Evaluating the effect of climate change on tree traits that could affect their suitability in CAF. For instance, accounting for phenological and physiological responses of trees such as bud burst and leaf development, changes in photosynthetic rates, positive carbon balance, hydraulic conductivity and reproduction to climate change will improve predictions of future species adaptations and subsequent functioning in CAF (Kramer et al. 2020).
- v. Modelling tree-crop combinations and pest and disease dynamics. Tree diversity, density, species and management are the key determinants of pest incidences (Nesper et al. 2017). For example, mature trees and sap exuding trees may reduce incidences of black coffee twig borer on Robusta coffee (Bukomeko et al. 2018). Climate change also seems to be altering the patterns in insect pests on trees and consequently some previously preferred shade trees have been identified as alternate hosts for pests. In Uganda's Robusta coffee, for example *M. eminii*, *A. chinensis* and *F. natalensis* that were previously choice species have been cited as a potential alternate or alternative hosts for the black coffee twig borer—a major insect pest of coffee in the country (Bukomeko et al. 2018; Dahlqvist 2016; Kagezi et al. 2019). *A. chinensis* has been specifically strongly discouraged by extensionists.

Below-ground interactions

Below-ground interactions mainly involve partitioning of water and nutrients. Agroforestry systems are expected to enhance water cycling processes (e.g. water infiltration and retention, reduced run-off) and hydrological ecosystem services through complementary root distributions (Ong and Swallow 2003). Trees, having deeper root systems than coffee promote water sharing mechanisms such as a redistribution of water in the soil profile through a process called hydraulic lift, or through shared mycorrhizal networks (Cardinael et al. 2020; de Carvalho et al. 2021).

On nutrition, the processes underpinning their acquisition in agroforestry systems include root distribution and plasticity, microbes, canopy capture and deep soil nutrient uplift, faecal inputs from perching bird or grazing animals, root exudates, leaf litter and pruning residues among others (Isaac and Borden 2019). In Brazilian coffee-agroforestry, continuous input of tree residues promoted changes to the soil organic matter with increase in total organic carbon, humic acids and light organic matter (Marinho et al. 2014). Nutrient acquisition is critical in view of carbon sequestration potential, which is very important for climate change mitigation.

The role of microbes viz. bacteria, fungi, actinomycetes and arbuscular mycorrhizal fungi and their potential to improve soil nutrition for coffee production is a subject of interest to many researchers. Studies have indicated that microbes may directly or indirectly contribute to plant nutrition (e.g. through the symbiotic relationship of mycorrhiza and biological nitrogen fixation) and reduction of pests and diseases (e.g. through enhancing plant defences), and hence have potential to increase plant tolerance to biotic and abiotic stresses associated with climate change (Usman et al. 2021). Research shows that tree roots attract their associated microbial partners from the local soil community, and, on the other hand, the associated microbial communities are shaped by both the host tree and local environment (Bagyaraj et al. 2015b). In Ethiopian Arabica-agroforestry systems for example, microbial species diversity differed in the rhizosphere of *Acacia abyssinica*, *A. gummifera*, *Ficus sur* and *Ficus vasta* (Dobo et al. 2018; Muleta et al. 2008). Studies in Brazil have also indicated that trees affect the vertical distribution of microbial

species along the soil profile (Cardoso et al. 2003). Generally, microbes in the rhizosphere of the trees are an important interaction that can influence and be influenced by coffee-agroforestry systems (Bagyaraj et al. 2015a; Beule et al. 2022). However, the effect of trees on the abundance, diversity and activity of microbial communities and how this may influence the coffee plants is still poorly understood in most Robusta contexts. Studies on nutrient use efficiency of mineral fertilization in coffee-agroforestry systems have not been found in literature. As indicated by Bayala and Prieto (2020), root competition between trees and coffee has not been well studied and needs to be well investigated for better management of agroforestry. Additionally, future climate scenarios need to be investigated since tree-crop root dynamics are dependent on the amount of available water in the soil, suggesting that competition may be intense between roots at low water availability (Bayala and Prieto 2020; Foxx and Fort 2019).

Therefore, the following questions could be formulated to evaluate below-ground tree-crop interactions:

1. How do different agroforestry trees contribute to soil bio-physical and chemical properties?

It is known that different species have different structural, biochemical and microbial properties. Consequently, it is envisaged that different trees could contribute distinctly to nutrient cycling and energy flow in CAF. A study in Brazil, for example, comparing coffee intercropped with *Grevillea robusta* or *Toona ciliata* suggested differential contribution to soil nutrients (dos Santos Bastos et al. 2023). So how different species contribute to improving nutrient availability, enhancing soil fertility, maintaining plant growth and development, accelerating soil organic matter formation, and increasing net carbon storage are key areas of research. This also has implications on the carbon sequestration potential of different coffee-tree agroforestry systems. It is also important to understand the nutrient release patterns of the trees, the percent of nutrients released that are taken up by the crop, and the fate of nutrients not taken up by the crop. Besides, nutrient content in litter is associated with particular soil microbial communities involved in the decomposition process. Disentangling nutrient acquisition strategies between trees and Robusta coffee is central to understanding positive nutrient interactions in CAF for improved low-input

agriculture. Digital innovations such as soil sensors have become great enablers and can accelerate such studies (Wadoux and McBratney 2021).

2. How do trees differ in their nutrient and water use in tree-crop systems and how does this affect coffee growth? Studies have suggested that tree species have different root structure and hence feeding zones, and differing water use patterns (Buyinza et al. 2019). These use patterns can be examined in view of competition between the trees and coffee, and how this supports crop growth. Currently, innovative non-destructive methods for studying root structure or water-use are available (Nadezhdina and Čermák 2003).

3. The diversity of microbes in the rhizosphere of different trees. The colonization of plants by microbiota is regulated by environmental factors, microbial activities, and active plant processes, for example, different leaf litter and root exudates have significant effects on soil microbial communities, which not only affect the diversity of microbial communities, but also influence the relative abundance of specific taxa in the vicinity (Du et al. 2024; Song et al. 2023). Cutting edge tools such as metagenomics have emerged as effective techniques for microbial diversity studies (Wadoux and McBratney 2021).

4. How the specific microbes contribute to the resistance of coffee to biotic and abiotic stresses and general crop health. Several microorganisms (including bacteria and fungi) are able to display plant growth-promoting capacities and/or biocontrol abilities toward coffee pests and diseases (Duong et al. 2020). Various mechanisms by which microbes promote growth, antioxidant activity, systemic induction of resistance or pathogen suppression have been suggested (Du et al. 2024). On the other hand, microbiomes have also been indicated to cause diseases in other plants (Du et al. 2024). However, the mechanisms by which the association becomes beneficial or detrimental needs more research in Robusta coffee.

5. Role of microbes in biogeochemical cycling and carbon sequestration, and the effect of climate change on microbial dynamics. Carbon sequestration by microbes is viewed in terms of their involvement in regulating multiple and distinct pathways for CO₂ inputs and losses, such as biochemical processes that could sequester CO₂, the capacity to sediment

carbonates, the rigid nature of their components and vegetative tissues, or the composition of complex substances that preserve carbon in the soil (Ahmed and McKay 2024). Conversely, global climate change affects the soil microbial community assemblages of many ecosystems (Classen et al. 2015). However, little is known about the effects of climate warming on the structure of soil microbial communities or the underlying mechanisms that influence microbial community composition CAF. The role of tree rhizospheric microbes in nutrient and water uptake of coffee such as mycorrhizal networks in water relations such as hydraulic lift as well as horizontal water sharing have been suggested (Ahmed and McKay 2024; Allen 2007) but is still unresearched in Robusta CAF.

Landscape mosaics

The outcomes of the interactions between trees and coffee can be context-dependent when the sign and/or magnitude vary spatially among different abiotic and biotic contexts (Chamberlain et al. 2014; Piculell et al. 2008). Generally, most observations in Uganda coffee systems have been limited to plot-level, which has implications on adoption and scaling. Yet, elsewhere, the effectiveness of agroforestry systems has for instance, been indicated to differ along geographic, edaphic, altitudinal and climatic gradient. In India and Brazil, for example, studies indicate significant interactions between shade, location, rainfall level and Robusta clones, suggesting that coffee-agroforestry systems, which may be similar with regards to tree and crop, may spatially differ (Piato et al. 2020). Studies have also indicated that tree-associated microbial interactions potentially coevolve in different ways in different environments, even when initially the genotypes of the interacting species are the same across all environments (Nantongo 2008; Piculell et al. 2008). This suggests that analysing the effects of a single environmental factor on coffee ignores the multiple interactions among the many factors that make up a particular niche. Therefore, understanding the distribution of these interactive effects against a range of environmental factors will enhance the ability to predict the productivity of coffee under different scenarios including climate change. This will also

enable the identification of areas where agroforestry systems may have the most potential to mitigate climate change to safeguard future coffee production or potential new areas for coffee production.

Therefore, research areas have been identified in view of landscape studies in Robusta-coffee agroforestry and these include:

- I. Understanding pedoclimatic relationships and biogeochemical (e.g. carbon) processes that could influence the interactions between trees and coffee. Edaphic and climatic conditions can affect plant suitability, distribution, production, physiology and chemical composition, and may not be mutually exclusive (Mensah et al. 2023). Although our knowledge of the response of trees to each of these individual conditions in spatial and temporal scales is significant, we know very little about how a combination of many of these factors, occurring simultaneously, that is multifactorial combinations impact trees and coffee. Developing a multi criteria analysis as a decision support tool to identify most suitable areas for the tree species could enhance the productivity of CAF. The suitability of tree species can be confirmed by the analytical determination of the soil and climatic properties. Conventional and digital remote sensing approaches offer unique opportunities for precise monitoring of climatic and edaphic variables (Wadoux and McBratney 2021).
- II. Prediction of future climate scenarios to identify new areas for introduction of coffee or sites that are more vulnerable to climate change. One of the major effects of climate change is the shift of suitability zones for the cultivation of specific crops, including coffee (Ovalle-Rivera et al. 2015). In Brazil, a study by Gomes et al. (2020b) predicted major shifts in areas suitable for coffee production that will take place within three decades. Accordingly, suitability shifts could happen to the associated trees (Balima et al. 2022), and indeed, de Sousa et al. (2019) suggested that changing tree species composition may be the best approach to adapt most of the coffee production areas to climate change.
- III. Acceleration of socio-ecological resilience in Robusta coffee farming communities. Global

changes are shaping social-ecological systems, threatening both biophysical and socio-economic environments as a whole. A relevant way to cope with disturbances is to promote social-ecological resilience through use of strategies that target the social-ecological system as a whole (Viñals et al. 2023). In this case, local communities will play a key role in both research and application. It has been suggested that approaching research activities through living labs, to collaboratively co-create, develop and test new technologies, products, services in real-life environments could contribute to better user acceptance and implementation of research outputs (Yousefi and Ewert 2023).

Conclusion

Overall, literature suggests the necessity of properly selecting agroforestry trees as well as managing above and below-ground resources for optimizing coffee production in the face of changing climate, but this will vary depending on the context of the agroforestry systems. Most of this information is missing in Uganda's Robusta agroforestry systems and scanty information is available in other Robusta growing areas. Although local perceptions and knowledge of agroforestry are generally viewed as crucial for sustainable adaptation in coffee-agroforestry systems, creating effective responses requires the integration of both scientific and local knowledge systems. Both of which are not well documented in Robusta coffee-agroforestry systems of Uganda. It should also be noted that optimal benefits will be derived when agroforestry systems are managed in synergy with other good agronomic practices such as use of improved coffee varieties, pest and disease management, pruning and weeding among others. Other important barriers to agroforestry adoption such as limited germplasm, appropriate communication and dissemination of research findings, and lack of capacity need to be simultaneously addressed. Policy support and decision-making for large-scale implementation of agroforestry systems are also hindered by lack or access to information. Demonstrating the impact of trees on coffee will require long-term demos and

funding. Gender and digital tools appear as key cross-cutting enablers for CAF research.

Competing Interests

The authors declare no competing interests.

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