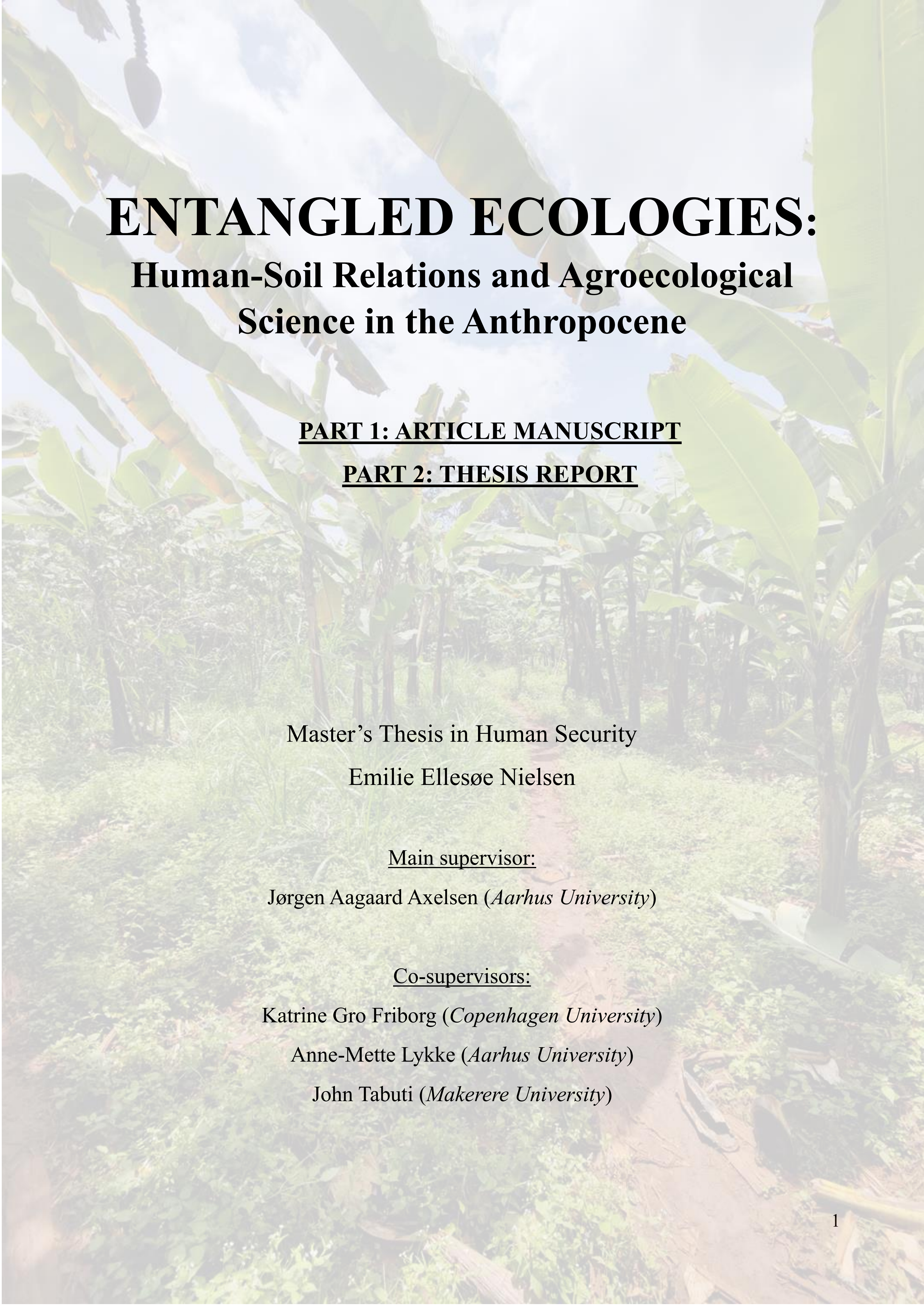

ENTANGLED ECOLOGIES:

Human-Soil Relations and Agroecological Science in the Anthropocene

PART 1: ARTICLE MANUSCRIPT

PART 2: THESIS REPORT

Master's Thesis in Human Security

Emilie Ellesøe Nielsen

Main supervisor:

Jørgen Aagaard Axelsen (*Aarhus University*)

Co-supervisors:

Katrine Gro Friborg (*Copenhagen University*)

Anne-Mette Lykke (*Aarhus University*)

John Tabuti (*Makerere University*)

Emilie Ellesøe Nielsen

(*B.Sc. in Biology, M.A. candidate in Human Security*)

Mail: ellesoenielsen@gmail.com

Student number: 20200518 | Exam number: 187115

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PART 1: ARTICLE MANUSCRIPT

Foreword:

The article manuscript, produced as part of this thesis, is intended for submission to the journal *Ecology and Society*[1]. This journal was selected due to its strong alignment with both the thematic focus and methodological orientation of my research. *Ecology and Society* is an interdisciplinary journal that explicitly welcomes contributions exploring the dynamics of social-ecological systems, with an emphasis on resilience, sustainability, and the co-production of knowledge - key concerns of this article. Methodologically, my article employs an integrated ethnopedological approach, combining qualitative methods with biological quantitative assessments of soil health. This reflects the kind of transdisciplinary, mixed-method research design that *Ecology and Society* explicitly supports. The journal actively encourages submissions that move beyond disciplinary silos and that engage local knowledge systems, participatory processes, and context-sensitive approaches—criteria that this article meets. Ecology and Society does not specify a strict word limit. However, most published articles are 6,000–10,000 words, including references. Given the article's mixed-methods design and rich empirical base, it is longer than a typical empirical submission.

[1] *https://ecologyandsociety.org/*

Youth, Agroforestry and Soil in Mount Elgon Uganda: An Ethnopedological Approach to Soil Stability and Erosion Risks in Montane Socio-ecological Systems

Emilie Ellesøe Nielsen

ABSTRACT

In Uganda's Mount Elgon region, land degradation and soil erosion pose critical threats to agriculture, rural livelihoods, and the functioning of montane socioecological systems. This article applies an ethnopedological approach—integrating qualitative ethnographic information with quantitative soil data, to explore how young small-scale coffee farmers perceive and engage with agroforestry (AF) as a strategy for soil conservation. The study highlights the hybrid knowledge systems, shaped by formal education, peer learning, and lived experience, that underlie farmer perceptions. Significant correlations between elevation, garden size and tree characteristics (e.g., density, aboveground biomass) and improved soil structure. Youth farmers recognise the positive impact of tree cover for erosion control. Despite widespread awareness and positive attitudes toward AF, adoption is constrained by land scarcity, intergenerational land control, and short-term financial pressures. Youths report limited access to land, lack of capital for seedlings, and fears that AF reduces food crop yields on small plots. If unaddressed, these constraints risk accelerating deforestation and increase food insecurity in already vulnerable communities. The study calls for targeted action to address long-term/short-term security dilemmas, land authority insecurity and enhance youth empowerment, close the gap between environmental knowledge and sustainable land-use practices.

Key words: Ethnopedology, soil, erosion, youth, agroforestry, montane, tropical, socioecology

INTRODUCTION

Land is an essential natural resource that supports socioecological well-being. However, it is increasingly facing soil degradation worldwide (Song *et al.*, 2018; IPCC, 2022), primarily due to anthropogenic and climatic factors (Mahata, 2021). Human activities - mainly deforestation, land-use change, and intensive farming beyond the land's capacity – drive the degradation of soils, compromising their stability, chemistry, and microbial life (Mganga, Razavi and Kuzyakov, 2016; Kroese *et al.*, 2020). Anthropogenic climate change accelerates land degradation through increased frequency and intensity of extreme weather events, such as flooding and droughts, which exacerbate soil erosion (Talukder *et al.*, 2021; Roy *et al.*, 2022). Conversely, land degradation - especially in deforested regions - contributes further to climate change by reducing the land's ability to sequester carbon, thus increasing greenhouse gas emissions (Song *et al.*, 2018; Roy *et al.*, 2022). Soil degradation compromises ecosystems, as degraded land loses its ability to support human and non-human life. Soils provide ecosystem services that support food production, water regulation, climate stabilization, and more - all foundational for human societies to thrive (Kraamwinkel *et al.*, 2021). As soil degradation undermines ecosystems, these services are compromised, leading to far-reaching social, economic, and environmental consequences, threatening food- and economic security, increasing vulnerability to natural disasters, and can lead to socio-economic instability, including migration and conflict (Talukder *et al.*, 2021).

Sub-Saharan Africa and Montane Ecosystems

Soil degradation directly threatens the livelihoods of rural populations, especially in low-income countries and regions like sub-Saharan Africa (SSA), where a large portion of the population relies on agriculture. Hence it exacerbates poverty by reducing agricultural productivity, which is a primary source of income for these communities (Barbier and Hochard, 2016, 2018; Slayi *et al.*, 2024; Tadesse and Hailu, 2024). Further, SSA is highly vulnerable to climate change, with projected increases in temperature and changes in rainfall patterns (Chapman *et al.*, 2020; IPCC, 2023), which will severely impact crop production and food security (Kotir, 2011; Adhikari, Nejadhashemi and Woznicki, 2015; Serdeczny *et al.*, 2017; Chapman *et al.*, 2020). Climate and land use interactions significantly influence ecosystem functions, with more severe impacts in montane zones (Peters *et al.*, 2019). Montane ecosystems in SSA face intense pressure from climate change combined with deforestation and land use changes primarily driven by agricultural expansion (Ensslin *et al.*, 2015; Hamunyela *et al.*, 2020; Ojoatre *et al.*, 2023), as seen in Uganda's Mount Elgon forests (Ojoatre *et al.*, 2023). Agricultural lands, particularly croplands, are highly susceptible to erosion, which is intensified by the lack of vegetation cover and poor land management practices (Fenta *et al.*, 2019; Wynants *et al.*, 2019). Deforestation accelerates soil erosion, reducing the percentage of water stable soil aggregates (WSA) and mean WSA diameter, which compromises soil structure and increases susceptibility to erosion (An *et al.*, 2008; Veldkamp *et al.*, 2020; Yaseen *et al.*, 2024)

Soil erosion in Mount Elgon

Soil erosion poses a serious challenge in Uganda's Mount Elgon area, stemming from both natural and human factors. The area's steep concave slopes and soil rich in clay, lead to instability and increased vulnerability to landslides and erosion. These "problem soils" exhibit significant expansive potential, rendering them liable to landslides even in the absence of human activities (Knapen *et al.*, 2006; Claessens *et al.*, 2007; Mugagga, Kakembo and Buyinza, 2012a). Land use changes, including deforestation and agricultural expansion, have increased soil erosion. The conversion of forests and woodlands into agricultural land has changed the soil's hydrological conditions, making the slopes more vulnerable to erosion and landslides (Claessens et al., 2007; Knapen et al., 2006; Mugagga et al., 2012b; Opedes et al., 2023). Soil destabilization increases due to high population density and land use practices like deforestation, which heighten the risk of landslides and erosion. (Knapen *et al.*, 2006; Broeckx *et al.*, 2019). Further, intense and frequent rainfall in the region exacerbates soil erosion. The combination of steep slopes, heavy rainfall and intense human impact lead to significant soil loss and landslide occurrences (Knapen *et al.*, 2006; Claessens *et al.*, 2007; Broeckx *et al.*, 2019). As populations grow rapidly and climate change becomes more pronounced, the region will face increased interannual variability in environmental vulnerability (Mubiru *et al.*, 2018; Wanyama, Kar and Moore, 2021). Although some soil and water conservation measures like trenches and grass strips are adopted, to adapt to the new climatic reality, their implementation is inconsistent and often insufficient to mitigate the erosion risk effectively (Bamutaze *et al.*, 2021; Opedes *et al.*, 2023)

Soil Aggregates

Soil aggregates are clusters of soil particles held together by stronger cohesive forces than those between adjacent aggregates (Lynch and Bragg, 1985; Dalal and Bridge, 2020). They are fundamental to soil structure, influencing its physical, chemical, and biological properties (Tisdall and Oades, 1982; Horn *et al.*, 1994; Mikha and Wills, 2021), and their stability is a key indicator of erosion susceptibility (Amézketa, 1999). Aggregate formation and stability result from both abiotic and biotic processes, including plant root growth, microbial activity, and physicochemical interactions (Garland *et al.*, 2024). Soil management practices strongly affect both the quantity and quality of aggregates, with organic matter being a primary determinant of aggregate stability (Williams and Petticrew, 2009).

Stable aggregates resist disintegration during rainfall, reducing the likelihood of soil particle detachment and transport by water. As a result, high aggregate stability is closely associated with reduced runoff and soil loss, making it a key factor in controlling erosion (Barthès and Roose, 2002; Nciizah and Wakindiki, 2015). WSA are commonly used as a proxy to assess soil erodibility and structural quality, offering a practical and cost-effective alternative to direct erosion measurements (Bryan, 1968; Mikha and Wills, 2021). Greater aggregate stability, or more stable aggregates. generally indicates improved resistance to erosion, enhanced water infiltration, better soil structure, and overall improved soil health(Barthès and Roose, 2002; Nciizah and Wakindiki, 2015).

Aggregate size distribution also plays a critical role in erosion dynamics(Nimmo and Perkins, 2018). Soil aggregates are typically classified into microaggregates (<250 µm) and macroaggregates (>250 µm), with macroaggregates being more responsive to land management practices (Mikha and Wills, 2021). Within the macroaggregate size range (up to 2000 µm), moderately large aggregates often improve water infiltration and reduce erosion risk (Tatarko, 2001). However, smaller macroaggregates are more easily detached and transported, contributing to higher erosion rates (Rai, Raney and Vanderford, 1954; Abu-Hamdeh, Abo-Qudais and Othman, 2006). However, very large aggregates (≥8000 µm) tend to have lower tensile strength and higher detachment rates, which may also increase erosion potential (Abu-Hamdeh, Abo-Qudais and Othman, 2006).

Agroforestry Effects on Soils

Agroforestry (AF), which combines trees with crops and/or livestock, has been recognised as a key management strategy for climate adaptation in SSA (IPCC, 2023; Quandt, Neufeldt and Gorman, 2023). Compared to both monoculture and various soil conservation methods, AF has demonstrated the most significant reductions in erosion (Muchane *et al.*, 2020; Du *et al.*, 2022). In Uganda, where forest degradation and soil erosion are prevalent, AF presents a promising solution to environmental issues while fostering rural development (Nkonya et al., 2011; Mbow et al., 2014). AF provides erosion control by the incorporation of organic matter (OM) through litterfall and pruning improves soil coverage and acts as a physical protective barrier against erosion, complemented by trees' interception (Muchane *et al.*, 2020; Fahad *et al.*, 2022). This is particularly beneficial in regions prone to heavy rainfall and erosion. AF has been shown to, significantly increase soil aggregate stability, by increasing soil organic carbon and nitrogen content through leaf litter and root systems (Gupta *et al.*, 2009; Chen *et al.*, 2017). AF show greater soil aggregate stability than monoculture systems, especially in the upper layers of soil (Saputra *et al.*, 2020). On Mount Elgon, the major causes of landslides include the loss of forest cover and the conversion of steep slopes for agriculture. To reduce landslide risks in this region of Eastern Uganda, increasing forest cover on steep terrains and restricting farming on critical slopes are essential measures (Knapen *et al.*, 2006; Mugagga, Kakembo and Buyinza, 2012c; Mande, Nseka and Mugagga, 2022).

Socio-Economical benefits from AF

AF offers numerous socio-economic benefits, particularly for rural communities. Firstly, AF systems improve resilience to climate change (Brown *et al.*, 2018; Satish *et al.*, 2024), and enhance ecosystem services such as soil structure improvement, water retention, and biodiversity preservation, which indirectly support socio-economic development (Köthke, Ahimbisibwe and Lippe, 2022; Mukhlis, Rizaludin and Hidayah, 2022; Girma, 2024). AF can significantly improve smallholder farmers' food- and economic security by improving yields, diversifying income sources and reducing reliance on single crops. This is achieved through the production of timber, non-timber products, intercropping and increased agricultural productivity (Duffy *et al.*, 2021; Mukhlis, Rizaludin and Hidayah, 2022; Girma, 2024). AF systems often incorporate traditional indigenous farming methods, These practices not only provide food security and income but can also strengthen spiritual connections and relationships with nature, thus aid in maintaining cultural heritage (Gonçalves, Schlindwein and Martinelli, 2021). AF stimulates cultural activities by promoting community engagement and cooperation in managing resources, fostering community and cultural identity essential for social cohesion in rural areas (Mukhlis, Rizaludin and Hidayah, 2022).

Youth – Soil Stewards of Tomorrow

Young people under 30 comprise more than 70% of Uganda's population (UBOS, 2024), and represent the next generation of farmers. Thus, young stewards, play a crucial role in shaping resilient landscapes that mitigate and adapt to climate change. Hence, the effective adoption and execution of AF initiatives rely on their readiness to participate in tree planting and their perceptions of. Their adoption of new technologies is affected by both extrinsic factors (e.g., farm characteristics, external environment) and intrinsic factors (e.g., knowledge, perceptions, attitudes) (Meijer *et al.*, 2015; Bennett *et al.*, 2018; Zossou *et al.*, 2020). The success of AF initiatives hinges on their perceptions and attitudes toward tree planting. As Bennett et al. (2018) note, local environmental stewardship is defined by who acts (actors), why they act (motivations), and whether they can act (capacity). Thus, understanding youth stewardship, therefore, requires attention not only to their motivations but also to the structural capacities that enable them to adopt and sustain agroforestry practices. Previous studies found that youth are more open to new developments and youth are generally more confident and interested in innovations, than older farmers (Galabuzi et al., 2021;Mukadasi et al., 2007). However, challenges such as land scarcity, inadequate access to quality seedlings, and limited capital inputs can hinder their participation in AF initiatives (Galabuzi *et al.*, 2021). Youth in Uganda represent a diverse group, facing age-independent opportunities and challenges, emphasising the necessity for context-specific and tailored knowledge (Declich *et al.*, 2022). While research on AF perceptions exists in SSA and Uganda, many studies are geographically limited, making it difficult to draw insights from specific farming context. Only one study was identified that explored young people's perceptions of AF in mountainous ecosystems with soil prone to erosion, which was based on quantitative research rather than qualitative (Bamwesigye *et al.*, 2024). Bamwesigye *et al.* (2024), found that a vast majority (92%) of youth in Mount Elgon believe that the cultivation farming system contributes to degradation, correlating with a willingness to engage in AF practices. However, this correlation alone is insufficient to fully understand the motivations behind these views. Farmers' understanding of the innovation and how they perceive its relevance and benefits significantly affect adoption (Meijer *et al.*, 2015). Understanding the elements influencing individuals' readiness to engage in AF is essential for developing efficient extension programs and policy initiatives that promote the uptake of AF practices (Franzel *et al.*, 2001). Hence, a qualitative research approach is considered essential to understanding the nuanced perceptions that shape perceptions and attitudes to AF. In socio-ecological systems, where human and natural environments are deeply interlinked, an integrated approach is necessary to address the complexities of resource management(Larcombe and Mitchell, 1998; Cerón Hernández *et al.*, 2020).

This study employs an integrated ethnopedological approach (Barrera-Bassols and Zinck, 2003), combining cultural understandings of soil with scientific assessment, using a mixed-methods design. The primary aim of this research is to investigate how young small-scale coffee farmers' perceptions of tree–soil relationships develop, relate to biophysical evidence, and shape their engagement with AF practices. To address this, the study investigates five sub-questions:

1) How do young farmers acquire knowledge about the relationship between trees and soil health?
2) What narratives and sentiments do youth hold about the effects of trees and specific species on soil quality?
3) What farm-level and environmental factors are associated with measured indicators of good soil structure?
4) To what extent do farmers perceptions correspond to the measured impacts of tree species on soil structure?
5) What motivates or discourages youth engagement in AF?

METHODS

Data collection

The qualitative methods included ethnographic fieldwork (Hammersley and Atkinson, 2019), semi-structured interviews (SSI), and focus groups discussions (FGD). The quantitative methods included field mapping, soil sampling, tree measurements, and structured interviews. This research followed a grounded theory framework, allowing for patterns and themes to emerge from the data. Qualitative and quantitative data were integrated using a convergent parallel design, where both data types were collected simultaneously, analysed separately, and then compared.

Ethnographic approach

An ethnographic approach was central to the methodology. Data was collected during immersive fieldwork conducted from September to December 2024 across three Ugandan districts: Kapchorwa, Bududa, and Mbale (figure. 1). I resided within these communities for extended periods, engaging in participant observation as the primary method. This involved closely observing farming practices, taking part in daily agricultural activities such as land preparation, planting, and harvesting, and attending community events and farmers' meetings. Throughout the fieldwork, I maintained detailed field notes and a reflexive journal to

Figure 1
Map of Uganda showing the study districts: *Kapchorwa, Bududa*, and *Mbale*, located in the Mount Elgon region of eastern Uganda.

record observations, informal conversations, and emerging patterns. Initial informal conversations helped refine the focus of the research and informed the design of a semi-structured interview guide. These informal engagements also served to triangulate and contextualise data obtained through formal interviews.

Semi-structured interviews and Focus groups

SSIs were conducted with young farmers in Kapchorwa, Bududa and Mbale, with 3-6 interviews completed in each location. These interviews took place within the interlocutor's garden and combined prepared questions with the flexibility to encourage a conversation about emerging insights. The semi-structured interview focused on (1) management practises (2) general AF perceptions, (3) perceptions of soil quality and trees, (4) the AF adoption process, and (5) future and alternative livelihoods (see Appendix A). Based on participants' responses, soil erosion was categorised using a three-point scale: 0: No erosion or only mild erosion occurring exclusively during the rainy season 1: Moderate erosion, predominantly observed during the rainy season. 2: Severe erosion during the rainy season, with occasional mild erosion also occurring during the dry season. After preliminary categorisation, interlocutors were asked whether they felt it was fair and accurate to assign their land to the identified category.

One FGD with young farmers practising AF was held in Sipi and Bududa, each involving 4 - 5 participants. The discussion was divided into two parts: (1) a general discussion, amongst the interlocutors, of perceptions of AF, including its challenges and benefits, facilitated by discussion cards based on the same questions as the interviews (see Appendix B); and (2) a ranking workshop where the group ranked the key barriers and motivations for young farmers to engage in AF, based on the challenges and benefits identified in part one.

Interlocutors for SSI and FGD were randomly selected from community Village Savings and Loan Association (VSLA) membership lists. Each member was assigned a number, and selections were made using a random number generator to ensure unbiased representation. The target group includes young people ($\leq$ 30 years). Among the interlocutors (n = 26), ages ranged from 17 to 30 years, with a mean age of 25.1 $\pm$ 4.6 years (mean $\pm$ SD). Interlocutors who have already or are planning to take part in FGD/SSI were excluded to prevent overlap.

Qualitative data analysis

All FGD and SSI recordings were transcribed, cleaned of personal information, and pseudonyms were assigned before coding data using NVivo (version 15) software. A thematic coding was conducted to identify recurring themes in SSI and FGD transcripts. These thematic codes were then applied in a content analysis through axial coding to explore relationships between themes and a sentiment analysis identifying attitudes (positive, neutral, or negative) toward key themes (See Appendix D). In a narrative analysis, I examined how individuals connect themes and concepts within their perceptions of AF to identify reoccurring structures and experiences, aiming to develop a conceptual framework based on data that identifies perceived cause-and-effect relationships.

Due to differences in phrasing, several conceptually similar issues were expressed using varied terminology. To enable comparison, manual coding was employed to identify and harmonize semantically similar entries. For example, “lack of funds for trees,” and “lack of capital for seedlings,” were grouped under “Lack of capital for tree seedlings”. This was done based on conceptual similarity andcontext from the discussion. The harmonized categories allowed for cross-group comparison and quantification of shared challenges. Each entry identified by participants was assigned a numerical score based on its rank, with higher-ranked items receiving higher scores. Specifically, the top-ranked challenge received the highest score (e.g., 22 for rank 1 in a list of 22), decreasing by one point per rank (e.g., 21 for rank 2, and so on). When conceptually similar entries were identified across both focus groups, their individual scores were summed to generate a score for the merged entry. This approach allowed us to quantify the relative importance of each issue across locations, with higher scores indicating greater perceived significance among participants. Each entry was assigned a common category name that captured the shared underlying issue. For barriers these were economic (e.g., lack of capital, unstable income), land and ownership (e.g., land access, youth rights), agricultural (e.g., tree shade, competition, pests), environmental (e.g., drought, climate effects), social or safety (e.g., neighbour conflicts, security risks), input and infrastructure (e.g., seedlings, pesticides). For benefits these were knowledge and experience (e.g., adoption of experience from others, knowledge access), social and cultural assets (e.g., youth employment opportunities, conflict mitigation), agricultural (e.g., improved soil fertility, reduced labour needs), economic (e.g., income from tree products), and environmental (e.g., shade provision, disaster prevention) and resources (e.g. medicinal plant, timber). The total score within each category were calculated, along with the *normalized importance*, defined as the average score per entry within a category, to indicate the relative importance of that category while adjusting for the number of entries it contains using these formulas:

$$\text{Total Score}_{\text{category}} = \sum_{i=1}^{n} \text{Score}_i$$

$$\text{Normalized Importance}_{\text{category}} = \frac{\text{Total Score}_{\text{category}}}{n}$$

Where n is the number of entries within a category, and Score_i represent the total score of the i^{th} category.

Soil Sampling:

Soil samples were collected from the gardens of each SSI interlocutor. Samples were taken from the top 10 cm at five points in each garden and combined into one composite sample per garden. Random sampling was conducted by identifying each garden's four corners and the centre. At each of these five points, a randomiser app was used twice: (1) to determine the direction to walk from the point and (2) to establish how many steps should be taken in that direction, with the maximum distance being approximately halfway between the corner and centre of the garden (figure 2). The soil was placed in a paper bag and stored at room temperature for 4 months before testing.

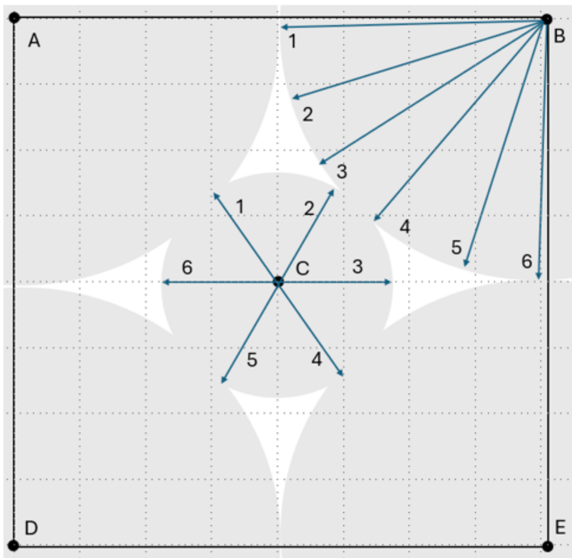

Fig. 2
Field soil sampling layout

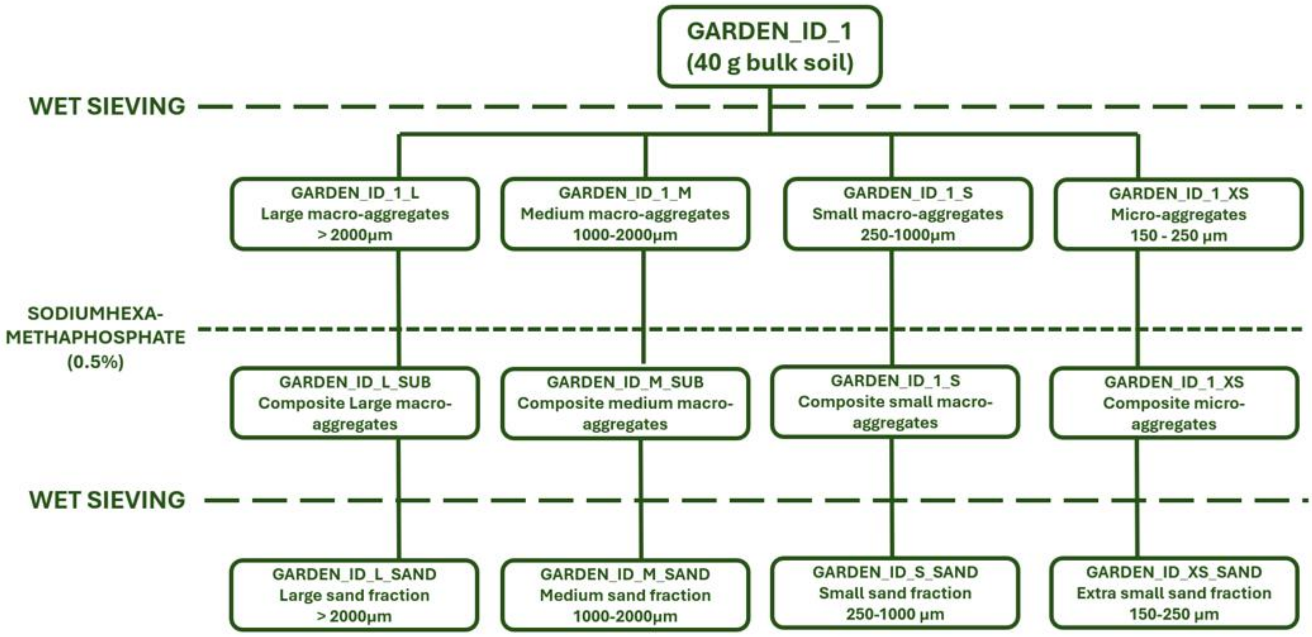

Fig. 4
WSA Fraction procedure flowchart

Wet Stable Aggregate Assessment

The proportion of WSA was measured to assess soil structural integrity and its resistance to breakdown under wet conditions, using the Barnwart method (Banwart and Sparks, 2017). Samples were dried at 40°C for 24h, placed in a tray and evenly distributed by gently rotating the soil mass. Three replicates of 40 g were then collected from each sample by extracting 8 g portions in a "W" pattern from different areas of the tray (figure 3). Lumps of soil larger than 2cm in diameter were removed along with debris and foreign materials such as plastics. The weight of each sample and container was recorded. Subsamples were manually wet sieved using a method based on (Elliott, 1986), in accordance with (Loaiza Puerta *et al.*, 2018) (figure 4). Soil was separated into four WSA fractions: WSA-L: Large macro-aggregates (>2000 µm), WSA-M: medium macro-aggregates (1000-2000 µm), WSA-S: macro-aggregates (250-1000 µm), WSA-XS: micro-aggregates (150-250 µm). Each replicate was submerged in deionised water and slaked for 5 minutes, and any floating organic material was

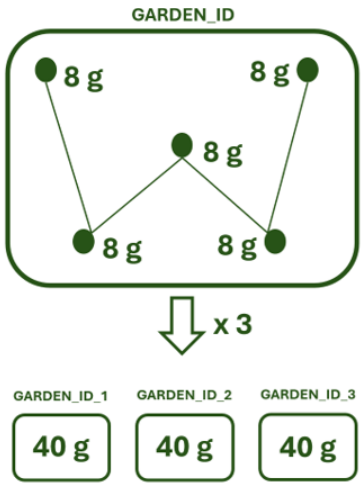

Fig. 3
Laboratory soil sampling

skimmed. Soil was manually sieved using 50 strokes over 2 m for the 2000 µm sieve, 40 strokes over 1m 10s for the 1000 µm sieve, and 30 strokes over 1m 20s for the 250 and 150 µm sieves. Aggregates were collected on pre-weighed aluminium trays, oven-dried at 105°C for 48 hours and weighed.

Both WSA and sand particles of identical size are captured on the sieves during sieving; therefore, a correction was applied to account for sand not contained within a WSA. Four composite fraction subsamples (>2000 µm, 1000-2000 µm, 250-1000 µm, 150-250 µm) were prepared for each sample. 5 g of each subsample was dispersed in a 0.5% sodium hexametaphosphate solution for 18h on a rotary shaker at 190 rpm, to dissolve WSAs. After dispersion, the fractions were passed through sieves corresponding to the lower limits of each sub-fraction (2000 µm, 1000 µm, 250 µm, and 150 µm), washed with deionised water, oven-dried at 60 °C, and weighed to determine the sand content retained on each sieve. The sand fraction mass was subtracted from the corresponding fraction in each replicate. The WSA% and aggregate size distribution was calculated using this formula:

$$WSA\% = \left(\frac{Fraction\ mass}{Total\ sample\ mass}\right) \cdot 100$$

Tree species and field mapping

The coordinates of each corner of the garden were recorded using the *Google Maps* app. and the composition of each garden was roughly sketched. All trees with a diameter at breast height (DBH) ≥ 5 cm were assessed using a caliper, and their height was estimated visually. The local and botanical names of each species were recorded, with identifications conducted in situ and validated collaboratively with farmers. Species within the genera *Eucalyptus, Cordia,* and *Ficus* were grouped under their respective genera due to morphological similarities that limited precise species-level identification in the field. All other genera included only a single recorded species and are therefore presented at the species level.

Based on immediate surface indicators visible soil erosion was categorised using a four-point scale: 0: No Erosion (Undisturbed soil, intact litter layer with no visible soil movement, and no erosion scars or plant damage). 1: Low Erosion (Minor bare spots, shallow rills, small erosion scars and occasional sediment deposits, and slightly disturbed vegetation; shrubs and crops remain upright.). 2: Moderate Erosion (Clear rills and early gullies, visible erosion scars, noticeable sediment deposits, exposed roots, some knocked-over or stressed shrubs/crops, and partial vegetation loss.) 3: Severe Erosion: (Prominent erosion scars, deep gullies, significant sediment accumulation, widespread bare soil, exposed subsoil horizons, extensive vegetation loss, and numerous shrubs or crops knocked over or uprooted.)

Quantitative data analysis

Garden size, slope and elevation were derived using QGIS software (v. 3.34.15). To quantify species diversity, the Shannon diversity index (H′) was calculated based on the relative abundance of each species using the formula

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

where S is the total number of species and p_i is the proportion of individuals belonging to the *i* th species (Magurran, 2004). Aboveground biomass (AGB) in kg was estimated for each tree using allometric model suitable for pan-tropical forests, developed by Chave et al. (2014), specifically:

$$\mathrm{AGB} = 0.0673 \times (\rho D^2 H)^{0.976}$$

where D is the diameter at breast height (DBH, in cm), H is the tree height (m), and ρ is the species-specific wood density (g/cm^3). Wood density values were obtained from African Wood Density Database (Carsan *et al.*, 2012).

Statistical analyses were conducted to assess the relationships between soil structural properties and a range of garden, tree, and management characteristics (see table 2). Continuous variables were assessed for normality using

Q-Q plots and for homoscedasticity using residual plots derived from linear models. Linearity was evaluated visually using scatterplots. The Pearson correlation coefficient was applied when both variables were continuous and met the assumptions of normality and linearity (parametric conditions). When these assumptions were not met, or when variables were ordinal in nature, the Spearman rank correlation was used (non-parametric). Wilcoxon rank-sum tests were employed to compare soil variables across binary categorical predictors. All statistical tests were evaluated using a significance threshold of $p \leq 0.05$. Results with $p \leq 0.01$ and $p \leq 0.001$ were considered highly and very highly significant, respectively. P-values equal to or greater than 0.05 were considered not statistically significant. Data processing and statistical analyses were performed using R Statistical Software (v. 2024.12.0) (See appendix C).

RESULTS

Formation of Knowledge and Understanding of Soil

Young farmers acquired knowledge about AF and its impact on soil health through a combination of knowledge transfer through family, formal education, and community-based training programs (e.g. from NGO or coffee companies). While formal education introduced the concept, hands-on experience and peer-to-peer learning played a crucial role in shaping young farmers' understanding of soil. Many interlocutors learned farming from their parents/guardians, where AF was already practised to some extent, making it an integral part of their agricultural knowledge. However, this intergenerational knowledge transfer involved either tree-integrated farming practices or not. interlocutors often observed successful practices from their neighbours and adopt them. Rose (17) mentioned that they saw others planting trees, which is why they also wanted to plant a few themselves. Or as one interlocutor explained: *"For us in these villages, we copy from others. I just copied from neighbours."* (Wilson, 25). Farmer groups provided platforms for learning and exchanging AF techniques among the community. Several interlocutors acquired knowledge from NGO's and development organisations which provided structured training on sustainable practices, such as trenching and tree planting. These organisations have also been facilitating peer-to-peer knowledge exchange. Many interlocutors also learned through personal experience by testing and observing the results in their own fields. Interlocutors refined their AF techniques based on firsthand observations of the relationships between trees, soil quality, and crop yields. One interlocutor said: *"The information I got right from my own garden—where underneath the tree, I see the plants do well."* (Miriam, 30). Another interlocutor observed that *"soil under trees - sometimes you experience it is very dark. But that one not in the trees, it is not very dark. Meaning that soil in trees is somehow more fertile than that one without."* (George, 17).

Environmental Changes and Their Impact on Soil

Although many interlocutors believed their soil to be of good quality and fertile, interlocutors saw erosion as a challenge, because it washes away fertile soil, leading to soil degradation and negatively impacting crop yields. Interlocutors reported significant impacts on soil health and farming outcomes due to increasingly extreme and unpredictable weather. One of the most pressing issues identified by interlocutors were increasingly heavy and prolonged rainfall, which most interlocutors associated with more frequent and severe erosion. As one interlocutor reflected, *"In previous years, the rainfall patterns were predictable. [...]. But now the weather pattern has changed. Where you expect rain, you receive sunshine. Where you* *expect sunshine, you receive rain"* (Miriam, 30). At the same time, interlocutors perceived extended dry seasons as becoming more common, resulting in water shortages and soil dryness. Wilson (25) explained that excessive droughts are a result of cutting down too many trees and emphasized that this practice should not continue.

The majority of farmers identified heavy rainfall and steep slopes as the primary causes of soil erosion, while many interlocutors linked deforestation and poor farming practices to worsening soil erosion and landslides. "*Our biggest challenge right now is disaster - the landslide,"* says Isaac (29), citing population growth and extreme rains as key factors. Another interlocutor elaborated, *"In the coming years we can get a lot of rainfall. Then, when people who stay at the top, they have not organized their gardens [made interventions to avoid soil erosion]. Now, the speed of water, and no planting of trees, bring those more landslides."* (Rose, 17). Interlocutors expressed concerns that without tree cover, soil becomes more vulnerable to erosion and waterlogging, reducing its capacity to support crops. One interlocutor warned, *"It [tree cutting] will affect the community, and then we shall lack our food. Food will be little"* (Wilson, 25).

Many interlocutors expressed a strong will and responsibility to conserve soil. However, the persistent deforestation in the area raised concerns amongst some. "*The community will face so much erosion, because most of them [other farmers], they don't want to plant these trees... Yes, and some of them are cutting them. So they will affect climate change, because most people cut trees. Even nowadays, they have placed soldiers there into the forests boundary whereby no one can enter the forest to cut the trees, but they are still cutting it."* (Brenda, 28). The interlocutors consistently mentioned AF as an essential strategy for safeguarding soil against climate change and thereby degradation and landslides. Jamil (24) expressed that practising AF could help restore the natural weather patterns, where rain falls and sunshine occurs when expected. They emphasized that if AF is not practiced, these normal weather patterns, will not return.

Perceptions of Trees-on-Farm and Its Impact on Soil Quality

Interlocutors consistently associated tree presence with increased soil quality, erosion control, and improved water management. In contrast, areas without trees, in contrast, suffered from accelerated erosion, leading to loss of topsoil and reduced productivity. Many described the soil beneath trees as darker, softer, and more fertile, and several interlocutors observed that soil near trees is richer than in open areas: "*the soil under the tree, that, it is always good, dark and fertile, but where there are no trees, soil is not always good. There is always little fertility where there are no trees."* (Jamil, 24). Many interlocutors emphasised that trees improve soil fertility, particularly through the decomposition of organic material such as leaves and fruits. An interlocutor explained that "*After shedding of the leaves, the leaves turn into manure, to increase fertility in the soil."* (Miriam, 30). Another interlocutor agreed, noting that *"There are some fruits there, whereby, when they fall down, they become fertilizers in the garden."* (Brenda, 28). Many interlocutors related this to *Coffea arabica* plants near trees yielding better quality and heavier fruits, indicating better soil conditions. *"Most soil is fertile in some areas where there are trees. Because it is fertile and the coffee is healthy" (Brenda, 28)*. Interlocutors observed soil structure as a key quality indicator, noting that trees enhance it. "*You find that we're under a tree and that the soils, the soils are bit dark and soft, that means that the* *soils are good for farming. But where you see no trees the soils, [...] you find the soils are very hard and you find that maybe such soils don't have enough water"* (Isaac, 29). The interlocutors' noted that trees help retain moisture in the soil, as they shade during the dry season and thus decrease evaporation. For instance, Miriam (30) sayed that *"because of less sunshine that goes down, there's some water, unlike the part which is bare - that it is exposed directly to sunshine. There is some a little water to no water."*. Further, she explained that the mulching layer protects the soil from direct sunlight, and the improved structure also improves water infiltration during the wet season. AF is commonly mentioned as an essential strategy for adapting soils to dry conditions. *"Trees help with infiltration of rainfall and in the formation of rainfall,"* (Mary , 28). Another added, *"[...] trees during dry season, is very important. They keep the soils with enough moisture, enough water to enable the crops."* (Isaac, 29). Hence, trees were perceived as regulating water across seasons *"Again, the rainy season, like the plant far from the tree, has a lot of water. Then this one, which is like, near the tree, it gets little water. Then during the dry season, the one far from the tree, actually does not have much water. But now, this one near the tree gets some water from the tree."* (Rose, 17). Interlocutors emphasized the value of trees for their root systems, which stabilize soil and prevent erosion during prolonged rainfall events. Brenda (28) explained *"The roots of these trees, they help up to harden [stabilize] the soil, whereby it controls soil erosion."*. Interlocutors highlighted that tree canopies reduce rain impact, while fallen leaves mulch the soil, protecting crops from heavy storms, as explained Isaac (29) *"[...] because under trees, you realise that the soil is not being hit direct. But where soils are open, there are no trees, there's direct rain drops onto the soil causing that erosion."*

Motivations for Trees-On-Farm

Participants cited soil conservation as a primary motivation for practicing AF, alongside various other benefits. Interlocutors reported that *C. arabica* grown near trees exhibits higher yields and better quality due to improved soil conditions. One interlocutor said, *"Now I planted those trees there to help in getting more yields and hold soil to avoid soil erosion."* (George, 17). Another interlocutor observed, "*The coffee is always good when you plant trees in the garden. The garden where we have planted trees is better than the garden where we have not planted trees."* (Brenda, 28). Another motivation for having trees on the farm were the additional economic benefits trees provide. Interlocutors recognised trees as a valuable resource for firewood, timber, and fruits. Miriam (30) explained, "*There are other values of having trees in the garden. One is that they provide firewood. The general cooking is done using firewood. Secondly, I can sell some trees for money. Then another one, I can use trees for constructing a house or for construction. [...] Some trees are a source of food. Then, for those avocados, there's a period when I sell and get some money."* While many interlocutors believed that trees positively influence coffee production, and they consistently reported that trees enhance coffee quality and yields, not all tree species were equally valued. Many recognised that successful AF requires careful management, including proper tree selection, spacing, and complementary soil conservation techniques such as mulching, intercropping, and controlled pruning to ensure that trees do not excessively compete with crops for soil nutrients and moisture. Interlocutors had selected tree species based on two key parameters: 1) provision of tree-based products (including fruits, timber, firewood), which provide, food, economic benefits and practical uses, and 2) erosion control and improvement of soil fertility. Many interlocutors planted and retained tree species that some species, particularly *Eucalyptus* spp., are valued for their fast growth and commercial potential, despite their negative impact on soil fertility.

Many interlocutors planted and retained tree species valued for their rapid growth and commercial potential, despite their perceived negative impact on soil fertility — particularly *Eucalyptus* spp. *Eucalyptus* spp. was generally seen as harmful to agriculture because it drains too much water and makes the soil dry. Some interlocutors removed *Eucalyptus spp.* from coffee gardens or kept it only for timber and firewood. Many trees were perceived to serve multiple functions, including timber, firewood, and fruit production. For example, *Persea americana* (avocado) and *Artocarpus heterophyllus* (jackfruit) were valued for providing both food and shade, while improving the soil quality. Fruit-bearing trees played a crucial role in the selection of tree species. Species such as *P. americana*, *A. heterophyllus*, and *Psidium guajava* (guava) were favoured for their dual benefits, providing both food for household consumption and income through market sales. Miriam (30) explained that *"some trees are a source of food. Then for those avocados, there's a period when I sell and get some money."*. Especially *Cordia spp*. was valued for its ability to bind the soil and prevent erosion, due to its strong root systems. Isaac (29) said, "*I prefer our local Kukyihili [i.e. Cordia spp.], those trees. Those are wonderful trees in preventing erosion and then in adding up to soil fertility."*. Trees that shed leaves, e.g. *Cordia* spp*., Ficus* spp*., Grevillia robusta,* and *Calliandra* spp*.,* were favoured because they contribute organic matter, natural fertilizers and improving soil texture and fertility. Interlocutors preferred *Cordia spp.* and *Ficus spp.* for their ability to grow large canopies that provide shade and protect both crops and soil from the impact of heavy rains or hailstones. Trees that provide shade were favoured, as they help regulate moisture levels, preventing excessive drying, especially in the dry season. One interlocutor noted that "*The reason for planting Gukuyu [Ficus* spp.*] and Kukyihili [Cordia* spp.*] is that they provide good shade, and the second is that they add manure after the leaves have dropped. After shedding of the leaves, the leaves turn into manure, to increase ferity in the soil."* (Miriam, 30)

Barriers and Challenges to Soil Conservation through Agroforestry

A major obstacle for young individuals were limited access to land. While some had inherited or received portions of family land, while others struggled to gain ownership, restricting their ability to plant trees. Jamil (24) explained, *"Some of my fellow youth, they feel like* AF*, but you have not got access to the pieces of land or plots to do the AF. That is one of the challenges to my fellow youth."* In many instances, parents still maintained authority over land decisions particularly for those on the younger end of the spectrum. While youth often had acquired knowledge about AF, their parents or elders resisted these changes. Young interlocutors experienced that earlier farming practices are deeply ingrained, and many older landowners were reluctant to allow tree planting, fearing it may interfere with crop production. Isaac (29) said: *"We [youth and parental generation] have differences in thinking, and mindset. The old generation, we expect them to be, knowing the importance of trees, but of course, when it comes to having them in the garden, they may not support".* Another interlocutor shared, *"The parents had it [the garden] with other plants, where they would plant these seasonal plants like beans, bananas and other things. But when they gave the land to me, I started introducing these trees." (Rose, 17).* Additionally, financial constraints made it difficult for young people to purchase their own land, further limiting their opportunities.

Food security and Land Scarcity

The role of shade in farming, as expressed by the young interlocutors, were multifaceted. The perception that many trees on farmland can negatively impact crop yield were prevalent, and thus many interlocutors expressed concern that too many trees can negatively impact food production. Interlocutors explained that trees compete with food crops and bananas for nutrients and reduce sunlight exposure, leading to stunted growth and smaller harvests. For instance, excessive shading were perceived to hinder food crops, such as *Musa* spp. (banana), *Fabaceae spp*. (beans) and *Zea mays* (maize). *"If I planted trees there, the trees will put shade in the garden, which can help only coffee, but not other crops, like beans and maize. Now that can lead to reduced yields from crops, leading to hunger."* said George (17). Miriam (30) explained further, *"Another side effect of having trees or* AF *in the garden, when the trees are many, sometimes they limit the sunshine. Limit the sunlight to enter the garden, and then the plants will now, instead of being to the normal size, they shoot up, and when they grow they are tiny."* Many interlocutors mentioned food insecurity as a consequence of trees-on-farm practices, while others mentioned it indirectly or/and confirm when asked. Several interlocutors highlighted that when land is small and trees are planted, it can lead to food shortages, as trees take up space that could otherwise be used for growing food. For instance, Miriam noted that *"when there are many trees, they bring food shortage. They promote food shortage in the garden"*. Interlocutors generally perceived AF to require more land than conventional farming, creating an additional challenge for young farmers who only have access to small plots. Rose (17) explained *"Because you see the land is small. I cannot put here trees"*. Many youths who were eager to practice AF simply did not have the available space to implement their visions. Brenda (28) explained that young farmers may hesitate to plant trees because of land constraints, due to food security concerns and emphasizes that people with small land holdings prioritize food crops, particularly *Musa* spp., over trees. Some interlocutors stated that they reduced the number of trees or removed trees to ensure adequate space for food crops. Another approach, to address this food insecurity, were acquisition of additional land. Several interlocutors mentioned that, if they had the means to get more land, they would separate food crops from *C. arabica* and trees, which would improve their food security and coffee yields. For instance, Miriam (30) shared: "*In case I get another wider piece of land - then I can now transfer the coffee to the other big plot, and then I now leave this one, which is near for food crops and some few trees. But since I do not have, therefore, now everything is confined in one place."*

Economic Constraints

One of the significant barriers preventing farmers from adopting AF were the need for immediate financial returns. Many interlocutors prioritized short-term economic survival over long-term sustainability, which significantly impacted their land-use decisions. Isaac (29) explained that *"the problem lies in their focus on things that bring immediate income. When you plant trees, there's no direct return right away, and that's the issue. They [fellow young farmers] need something productive in the short term*." While trees are perceived to improve the field and contribute to agriculture in the long run, short-term needs often overshadowed the long-term benefits of AF. Since trees do not generate income immediately, many interlocutors hesitated to invest in them. Interlocutors often preferd growing food crops like

Table 1
Ranked challenges and benefits related to agroforestry adoption as identified by participants in two focus groups. Challenges were categorized based on whether they were perceived as barriers (factors discouraging adoption) or motivations (factors encouraging adoption) and then ranked according to their importance

	Barriers		**Motivations**	
	Focus Group 1	**Focus group 2**	**Focus Group 1**	**Focus group 2**
1	Lack of capital for seedlings	Lack of money to buy land	Trees give income to buy food	Soil erosion control
2	Lack of short-term income	Lack of land	Trees provide healthy food (e.g. fruits)	Trees create income
3	Lack of land	Lack of funds for trees	Trees provide fresh air	Trees increase yields
4	Climate change decreases rainfall in the dry season	Some trees make the soil dry	Trees provide timber	Adoption of experience from other people
5	Drought	Uncertainty about land ownership/land grabbing	Trees provide shade	Trees prevent coffee berries from falling during heavy rain
6	Soil erosion	Danger of falling trees	Trees act as windbreakers	Trees are habitats for bats, which prevents pests
7	Tree theft	Destruction of property, because of falling trees	Trees can be used for medicine	Trees make food for animals
8	Trees spread pests and disease	Delayed / unstable income from trees	AF gives less labour	Trees can be fences to avoid trespassing
9	Lack of food diversity in agroforestry	Shade from trees decreases the yield of food crops	Knowledge from school	Deciduous leaf gives soil fertility
10	Having trees amongst coffee creates the need for separate production of food	Drought	Old knowledge	Trees reduce the need for fertilisers
11	Shade decreases the yield of food crops (e.g. matooke)	Lack of access to seedlings	-	Trees prevent landslides
12	Trees fall on coffee and other crops	Trees drain water from top topsoil	-	Trees provide firewood
13	Threats from neighbours because of the trees create insecurity	Trees compete with food crops, giving a lower yield	-	Trees provide fresh air
14	Tree branches fall on crops and people	Trees reduce cash crop production (e.g. onions)	-	Trees provide construction wood
15	Neighbour boundary conflicts	Pests	-	Trees provide timber
16	Trees make it easier for people to hide	Parents own the land, so the youth can't decide	-	Trees prevent disease because of lower temperatures
17	Tree delay income	Trees give a lower temperature in the rainy season	-	Trees produce food
18	Tree shade decreases yields	Heavy rain makes trees fall on the coffee	-	Tree shade prevents pests
19	Lack of pesticides	Trees compete with other plants	-	Trees reduce the impact/force of heavy rain on the soil *

* Ranked lower respectively: Falling berries from trees provide soil fertility, Trees provide fruits, Trees act as windbreakers to protect crops, Trees can add nutrients via. Root nodules (e.g. Calliandra), Trees produce rain/dew in the dry season, Trees provide charcoal, Knowledge on AF from school, Trees keep water in the dry season, AF gives youth employment, Trees prevent floods, Trees indicate the garden boundary to avoid neighbour conflicts, Trees give shade for humans

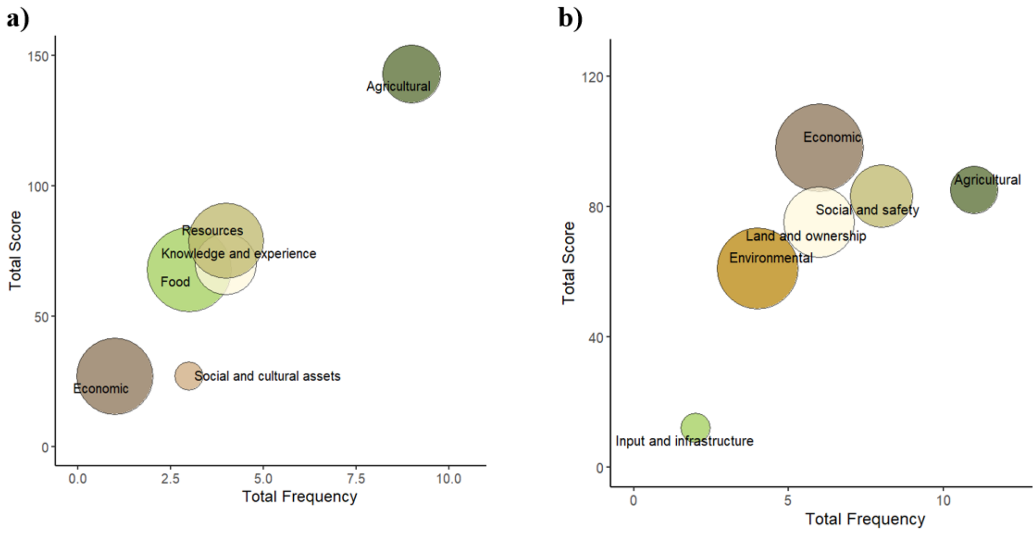

Fig. 5
Bubble charts representing **a)** perceived barriers and **b)** benefits of agroforestry identified during focus group discussions. Each bubble represents a thematic category, distinguished by colour. The X-axis shows the total frequency of mentions within each category, and the Y-axis shows the total cumulative score assigned to that category. Bubble size indicates normalised importance, calculated as the average score per barrier or benefit. The colours of the bubbles represent each category

they provide quicker returns, and their cash flow requirements demand crops that can be harvested within months rather than having to wait years for timber or fruit trees to become profitable. Many interlocutors noted that they, or others, had cut down their trees to pay for necessities such as school fees or food. Hence, interlocutors prioritized fast-growing crops over trees, and fast-growing tree species over slow-growing species. Isaac later said: *The other day, when we passed the person around the health centre, we said: "they are trying to give us trees for the farmers to plant". But somebody says: "Ah! trees are very good, but is there anything attached? Is there some money?". Yeah, there's no money. So, the person will not plant [...] They [youth] receive knowledge every now and then, but implementation is the problem".* Lack of initial capital further exacerbated this challenge, preventing youth from purchasing seedlings, fertilizers, tools or other necessary inputs that could enhance soil fertility and structure. Many interlocutors also mentioned that the cost of purchasing tree seedlings is a major issue, making it difficult for young farmers with little money, to establish AF systems. Some struggled to access specific tree species they wished to cultivate.

Focus Group Rankings

Focus group (FG) 2 ranked the challenges according to their perceived overall importance. In contrast, FG 1, in contrast, approached the ranking task chronologically. The group agreed that the most important barriers were those that arise earliest in the AF process, reasoning that unless these initial obstacles are overcome, later challenges become irrelevant. Table 1 summarizes the ranked barriers and motivations as identified by both groups. Among barriers (figure 5a), *economic* barriers emerged as the most prominent, with high frequency, the highest total score, and the largest normalized importance. *Environmental* and *land and ownership* were also notable, both in frequency and total score, though with slightly lower normalised importance than economic barriers. *Social and safety* barriers also scored moderately high,

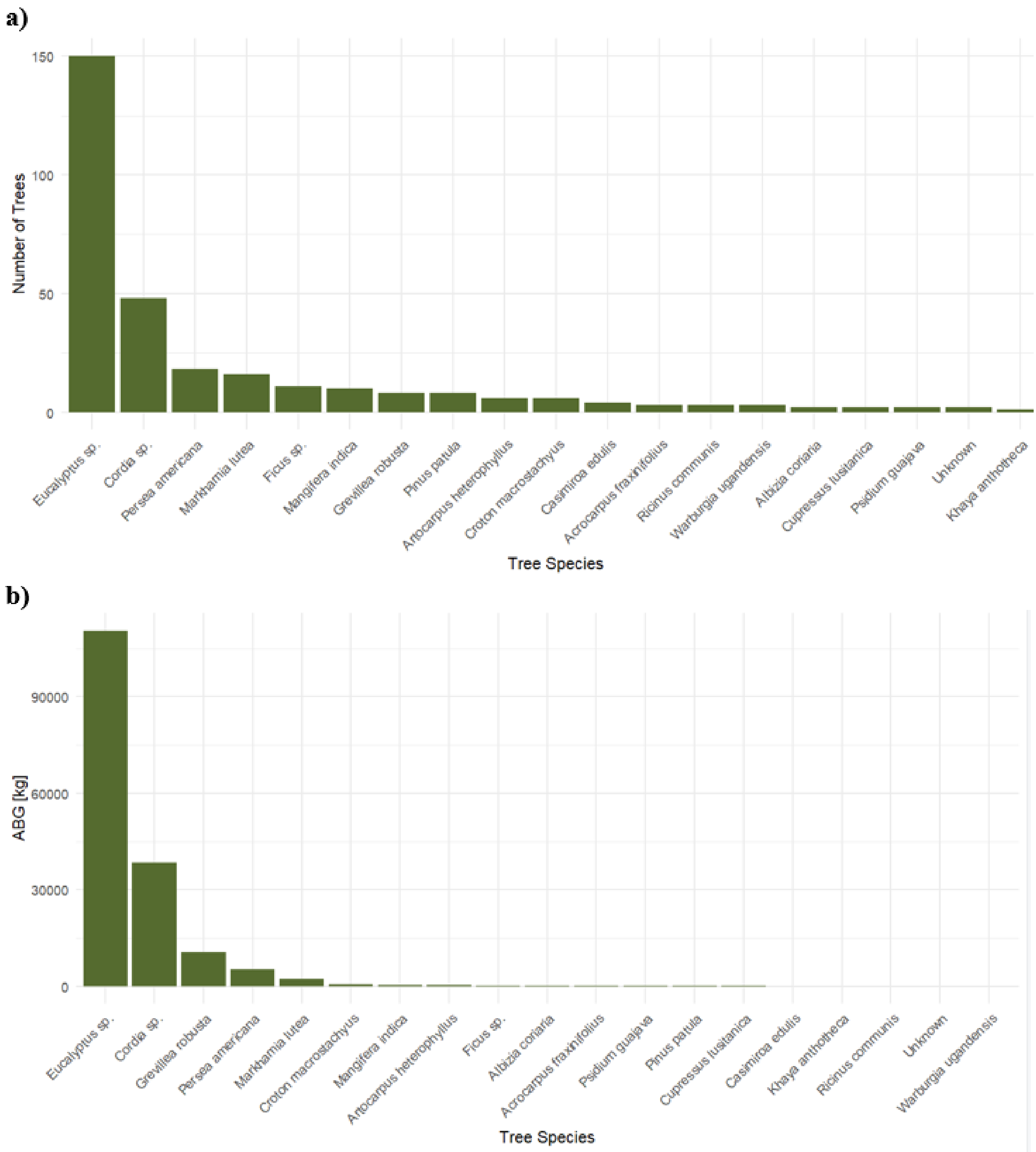

Fig. 6

a) *Abundance of tree species and* ***b)*** total aboveground biomass (AGB) per tree species recorded across the study area. *Eucalyptus, Cordia, and Ficus species are combined under their respective genera.*

while *Resources* were the least cited barrier, with low frequency and total score. For the benefits (figure 5b), *food* and *economic* benefits ranked highest in normalized importance, respectively. Although *agricultural* benefits stood out with the highest frequency and cumulative score, they had a comparatively lower normalized importance. *Infrastructure and* *resource* benefits also received relatively high scores, while *social and cultural assets* were less frequently cited and scored lower.

Garden, farmer and tree species characteristics

Garden sizes among interlocutors varied widely, ranging from 233 m² to 7679 m², with a mean size of 1889 ± 1953 m². The gardens had a mean tree density of 148,0 ± 129,5 trees pr. hectare. All interlocutors have planted trees to reduce erosion, and many have also adopted additional soil management practices such as mulching (used by all farmers), constructing trenches or terraces (used by 70.5% of farmers) and minimising digging during the rainy season. The most dominant tree species by far is *Eucalyptus spp*., with 150 individuals, significantly outnumbering all other species. The second most common species is *Cordia spp*., with just under 48 trees, followed by *P. americana, Markhamia lutea,* and *Ficus spp*., each with respectively 18, 16 and 11 trees. A long tail of species, including *Mangifera indica, G. robusta, A. heterophyllus,* and others, each occur at much lower frequencies (fewer than 10 individuals each). Several species, such as *Khaya anthotheca, P. guajava*, and Unknown, were recorded only a few times (1–3 individuals) (figure 6a). *Eucalyptus spp.* alone accounted for 110.428 kg of total AGB, dominating the tree biomass of the area. *Cordia spp.* and *G. robusta* followed, contributing with 38.428 and 10.514 kg, respectively. All other species, including commonly cultivated trees such as *P. americana* and *M. lutea,* contributed relatively minor amounts to the total biomass pool (figure 6b).

WSA and perceived erosion

All farmers report experiencing soil erosion, particularly during the rainy season. 23.5% reported minimal erosion, while the majority (47.1%) of respondents perceived moderate erosion, and 29.4% reported severe erosion (figure 7).

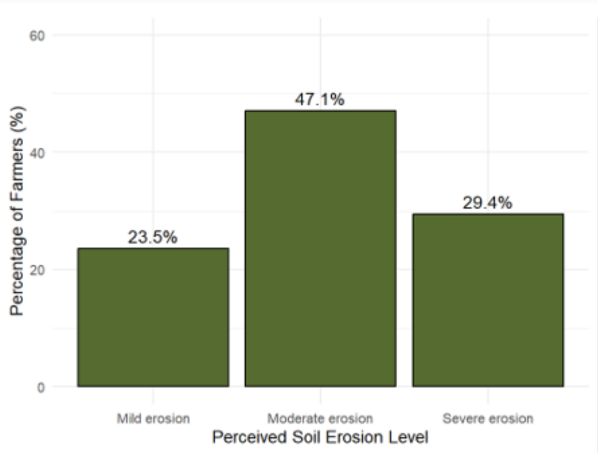

Fig. 7.
Perceived soil erosion risk among surveyed farmers (*n = 17*), based on interviews. Farmers ranked erosion in three categories: 0) mild erosion, only during the rainy season; 1) moderate erosion, mainly during the rainy season; and 2) severe erosion during the rainy season, with occasional mild erosion in the dry season.

The soil included an average of 60,9±12.3% WSA, across the sampled sites (figure 8a). WSA-S exhibited the highest mean WSA values at 30,7%, WSA-L showed moderate WSA percentages, with a mean of 15,5±10.7 % and a wider distribution, while WSA-M and WSA-XS had the lowest mean WSA values of respectively 7,9±3.8 and 6,8±2.7% (figure 8b).

Statistical Relationships between Soil Structure and Associated Variables

Garden size exhibited a significant, moderately to strongly negatively correlation with WSA-L% (p = 0.01), suggesting that larger gardens may be associated with reduced stability of large soil aggregates. Elevation was strongly positively and very highly significant correlation with WSA% (p = 0.001), indicating that soils at higher elevations tend to exhibit improved structural stability due to greater proportions of WSA, particularly in the medium (p = 0.002) and small size fractions (p = 0.001). Visible erosion showed a moderately positively correlation with perceived erosion (p = 0.04), suggesting that farmers' perceptions broadly reflect observable erosion indicators. However, there was no significant relationship between perceived erosion and any of the WSA metrics

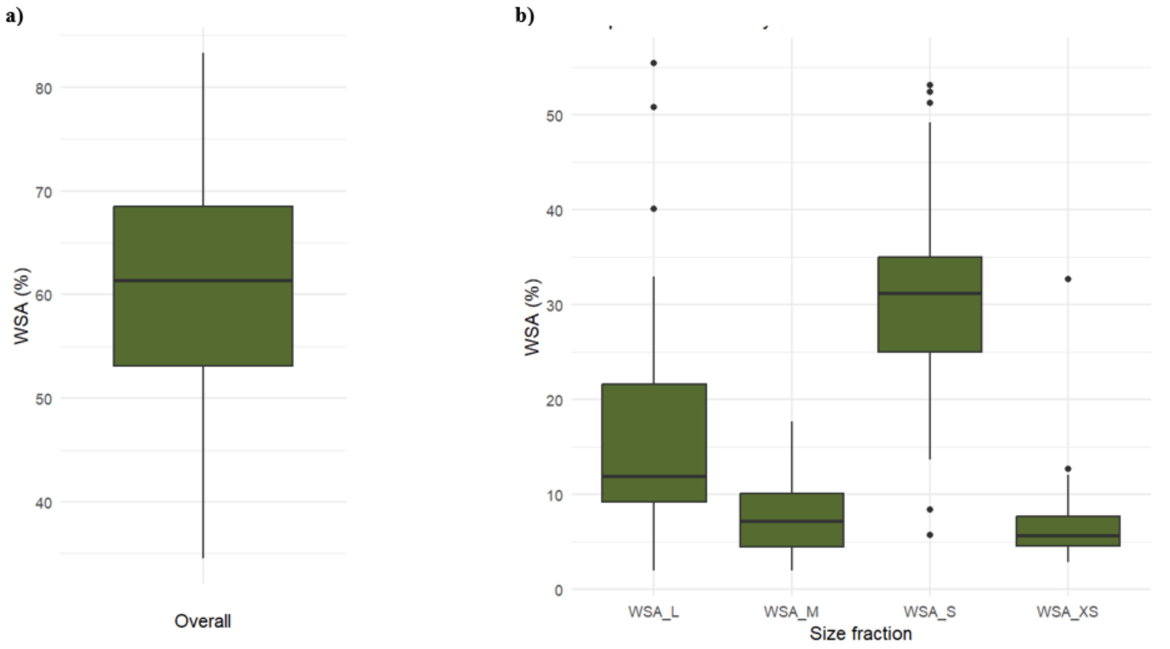

Fig. 8.
a) The distribution of overall water-stable aggregate percentage (WSA%) across all soil samples.
b) fractions of WSA separated by aggregate size classes (large, medium, small, and extra small).

Table 2
*Statistical relationships between garden/farmer characteristics, tree characteristics, and management practices with different soil water stable aggregate (WSA) size fractions and perceived erosion. Variables were tested using Pearson correlation (P), Spearman rank correlation (S), or Wilcoxon rank-sum test (W), as appropriate. Correlation coefficients (r for Pearson, ρ for Spearman) were reported alongside p-values to indicate the strength and direction of associations. P-values indicate the significance level (*p ≤ 0.05, **p ≤ 0.01, **p ≤ 0.001).*

	WSA%			WSA-L%			WSA-M%			WSA-S%			WSA-XS%			Percieved erosion		
	P	r / ρ		P	r / ρ		P	r / ρ		p	r / ρ		p	r / ρ		p	r / ρ	
Percieved erosion	0.31	-0.3	S	0.74	-0.09	S	0.09	-0.4	S	0.37	-0.2	S	0.6	-0.14	S			
Garden/farmer characteristics:																		
Farmer age	0.74	-0.09	S	0.72	0.09	S	0.72	0.09	S	0.49	0.18	S	0.74	-0.09	S	0.74	-0.09	S
Garden size	0.97	0.01	S	0.01**	-0.59	S	0.71	-0.10	S	0.02	0.58	S	0.31	0.26	S	0.72	-0.09	S
Slope	0.63	-0.13	S	0.27	-0.28	S	0.23	-0.31	S	0.48	-0.18	S	1.00	0.00	S	0.10	0.41	S
Elevation	0.002**	0.69	S	0.90	-0.03	S	0.01**	0.63	S	0.02*	0.56	S	0.17	0.35	S	0.32	-0.26	S
Visible erosion	0.25	-0.30	S	0.27	-0.29	S	0.43	-0.21	S	0.44	-0.20	S	0.27	0.28	S	0.04*	0.50	S
Tree characteristics:																		
Tree density	0.49	0.18	S	0.05*	0.49	S	0.34	0.25	S	0.93	0.03	S	0.62	-0.13	S	0.92	-0.03	S
AGB density	0.44	0.09	S	0.72	0.09	S	0.09	0.43	S	0.05*	0.49	S	0.52	0.17	S	0.02*	-0.55	S
Shannon index	0.08	-0.44	P	0.98	0.01	S	0.04*	-0.50	P	0.34	-0.25	S	0.65	-0.12	S	0.64	0.12	S
Cordia spp. density	0.07	0.46	S	0.03*	0.52	S	0.05*	0.48	S	0.76	0.08	S	0.87	-0.04	S	0.08	-0.44	S
Ficus spp. density	0.001***	-0.71	S	0.65	-0.12	S	0.02*	-0.56	S	0.31	-0.26	S	0.72	-0.10	S	0.35	0.24	S
Grevillea robusta density	0.42	-0.21	S	0.37	0.23	S	0.70	-0.10	S	0.55	-0.16	S	0.11	-0.40	S	0.52	0.17	S
Mangifera indica density	0.35	-0.24	S	0.27	0.28	S	0.84	-0.05	S	0.42	-0.21	S	0.32	-0.26	S	0.25	0.29	S
Eucalyptus spp. Density	0.0495*	0.48	S	0.92	0.03	S	0.047*	0.49	S	0.01**	0.62	S	0.32	0.26	S	0.20	-0.33	S
Markhamia lutea density	0.05	-0.48	S	0.51	-0.17	S	0.49	-0.18	S	0.68	0.11	S	0.93	0.02	S	0.66	-0.12	S
Persea americana density	0.99	0.00	S	0.37	0.23	S	0.50	0.18	S	0.67	-0.11	S	0.99	0.00	S	0.75	-0.08	S
Other management practices:																		
Manure application frequency	0.52	-0.17	S	0.43	0.21	S	0.64	-0.12	S	0.03*	-0.52	S	0.99	0.00	S	0.89	0.04	S
Weeding frequency	0.29	0.27	S	0.52	-0.17	S	0.38	0.23	S	0.07	0.45	S	0.54	0.16	S	0.55	-0.15	S
Trenching/terracing	0.23	-	W	0.38	-	W	0.06	-	W	1.00	-	W	0.23	-	W	0.13	-	W

P	-0.8 to -1.0	-0.6 to -0.8	-0.4 to -0.6	-0.2 to -0.4	-0.2 to < 0	> 0 to 0.2	0.2 to 0.4	0.4 to 0.6	0.6 to 0.8	0.8-1.0
r/ρ	≥ 0.05	≤ 0.05 *	≤ 0.01 **	≤ 0.001 ***						

($p > 0.05$). Among tree-related variables, tree density was moderately positive correlated with the stability of WSA-L% ($p = 0.05$), while AGB density was moderately positive correlated to WSA-S% ($p = 0.05$) and negatively correlated with perceived erosion ($p = 0.02$), suggesting that more trees and greater tree biomass may contribute to both improved soil structure and reduced erosion perception. However, Shannon index was moderately negatively correlated with the stability of WSA-M% ($p = 0.04$), suggesting that higher tree diversity may correspond with reduced structural stability in this fraction. Some species-specific effects were also evident: *Cordia* spp. density was moderately positively correlated with WSA-M% ($p = 0.05$), and WSA-L% ($p = 0.03$). *Eucalyptus* spp. density was moderately positively correlated with both WSA-M% ($p = 0.03$) and overall WSA% ($p = 0.05$), indicating that higher densities of *Cordia* spp. and *Eucalyptus* spp. were associated with greater proportions of medium to large-size WSA, and that *Eucalyptus* spp. was also associated with higher overall aggregate stability. Meanwhile, *Ficus* spp. density showed a highly significant and strongly negative correlation with overall WSA%, and a moderate negative correlation with WSA-M%, suggesting a potential adverse effect on soil aggregate stability, particularly in the medium size fraction. Other management practices also influenced soil aggregation. Manure application frequency was negatively correlated with WSA-S% ($p = 0.03$), indicating that higher frequencies of manure application were associated with lower proportion of small WSA (table 2)

DISCUSSION

Learning from the Land and Each Other

Young farmers acquire knowledge through experiential learning—actively experimenting and observing the impacts of trees on soil fertility, moisture retention, and erosion control. Interviews revealed a nuanced understanding of tree-soil dynamics, grounded in farmers' daily, embodied interactions with the land. These findings resonate with Hockett and Richardson (2018), who documented smallholders in Malawi engaging in adaptive experimentation in response to environmental stressors and resource constraints. In the Mount Elgon context, such adaptation appears in comparisons between soil under tree canopy and open fields, trials of new AF species and observations of neighbouring farms. Although not labelled as "experiments," these actions reflect iterative, learning-based innovation that shapes evolving understandings of soil health. Both contexts illustrate hybrid knowledge systems, where experiential knowledge intersects with inputs from NGOs, development projects, and extension agents. Some farmers demonstrate a strong grasp of agroecological principles, often informed by formal education, extension services, and NGO training. Cadger et al. (2016) show that farmers affiliated with formal information sources and development interventions are embedded in more diverse social networks, facilitating knowledge diffusion beyond direct project participants. This study also finds that soil knowledge is shaped by farmers' social positions and generational contexts, with peer-to-peer exchange emerging as a vital mode of knowledge transfer. This echoes Izuchukwu et al.'s (2023) review study across SSA, which underscore the role of farmer-to-farmer communication, especially in rural contexts, in promoting sustainable agricultural practices through peer learning and imitation. The peer imitation observed here ("we copy from others") parallels findings by Kiptot et al. (2006) in western Kenya, where kinship networks were central to AF knowledge sharing, though broader community structures—such as farmer groups and social networks—also played key roles. Socially active farmers, involved in multiple groups or holding community roles, were more likely to share knowledge beyond their families. This reflects Isaac et al. (2007), who highlight informal advice networks as crucial to AF knowledge transfer in Ghana. Their study identifies a *core-periphery* network structure, where central, community-engaged farmers serve as bridges between institutional and local knowledge or what Cadger et al. (2016) term *bridging ties*, enabling diffusion beyond direct recipients of formal interventions and embedding agricultural learning within social relationships. Intergenerational knowledge transfer emerged as a key pathway, with young farmers inheriting practices from parents or elders. This echoes Occelli et al. (2021), who found that traditional household knowledge significantly influences soil management capacity, particularly in low-input, marginal settings. Yet the depth and relevance of inherited knowledge vary according to the extent of prior agroforestry practice, highlighting disparities in youth understanding. However, in the context of Mount Elgon, this transmission is neither linear nor uncontested. Several farmers reported tensions around AF adoption. While younger members increasingly access external knowledge sources, older generations often regard this outside knowledge with scepticism, favouring locally rooted traditions.

Seeing is Believing - Soil Tells the Story

Across interviews, youth attitudes toward AF were highly positive, and trees were consistently recognised for their role in retaining nutrients, moisture, and regulating microclimates. Tree cover was viewed as a key strategy to prevent erosion, with the protective function of roots and canopies frequently mentioned. Perceived soil erosion was negatively correlated with AGB and positively with visible erosion, however it was not correlated with WSA metrics. This indicates that farmers associate high erosion with lower tree biomass and rely primarily on visible surface indicators rather than subsurface processes, supported by the interviews, where farmers often noted immediate cues observable during or after rainfall. While visible erosion reflects short-term surface impacts, WSA measurements can provide insights into longer-term soil stability (Tatarko, 2001). Because visible erosion aligns with sensory experience, it directly influences perceived erosion risk, as individuals rely on this as their primary indicator, supporting the conclusion that visible indicators largely drive perception.

However, WSA metrics were not significantly correlated with either perceived or visible erosion, suggesting a disconnect between observed surface conditions and deeper soil structural stability, indicating that visible erosion may not serve as a reliable proxy for WSA. However, WSA metric is only one indicator of soil erosion, capturing only one aspect of a complex process influenced by various factors (Adnan, Aldefae and Humaish, 2021). Remote sensing techniques, methods that also depend on surface-level indicators, have demonstrated considerable efficacy in estimating soil erosion rates (Seutloali, Dube and Sibanda, 2018; Beniaich *et al.*, 2022). Although image-based assessments offer valuable quantitative insights, they represent only a fraction of the environmental complexity perceived through direct interaction with the land. In contrast, farmers embodied tacit knowledge incorporates rich sensory, experiential, and contextual information acquired over time. Okoba (2005) demonstrated that farmers' erosion indicators effectively map soil degradation and estimate yield loss, producing results comparable to scientific assessments and that excluding farmers from such assessments limits conservation engagement. Hence, the lack of correspondence between WSA metrics and farmers' perceived erosion should not necessarily be seen as a lack of understanding by farmers, as it may highlight the limitations of relying solely on technical indicators. Studies evaluating the accuracy of farmers' use of visible, on-the-ground indicators to estimate soil erosion have been limited. However, Bamutaze *et al.*, (2021) found that farmers' perceptions of soil erosion risk only partially aligned with the RUSLE erosion risk model (Renard *et al.*, 1997), and in many cases, underestimated the severity of erosion. Many farmers rated their land as having low to moderate erosion risk, even when the model showed it was severe. However, in some high-risk cases, there was a reasonable match, with farmers identifying the risk as either severe or very severe. Despite high erosion rates, most farmers still considered their land to be fertile and productive. This short-term productivity may still be good, masking the long-term damage from erosion.

The role of Local Epistemologies

Farmers' perceptions may not exactly match soil metrics, but they are not inaccurate. The negative correlation between perceived erosion and AGB, may reflect the findings that greater AGB improves soil structure (WSA) and reduces erosion, as supported by scientific literature (Gyssels and Poesen, 2003; Milodowski, Mudd and Mitchard, 2015). Their knowledge socially situated and emerge from community networks, that reinforce consistent and collectively held perceptions, fostering a localized epistemology that is both lived and learned. Their focus on tree cover may reflects local epistemologies in which trees are believed to play a protective role against erosion. This alignment suggests that locally grounded tacit knowledge systems, still reflect important ecological realities, highlighting the hybrid nature of farmers' knowledge. This aligns with previous literature documenting that risk perception is not solely based on scientific data but also incorporates local knowledge and cultural worldviews (Stoffle and Minnis, 2008). Local epistemologies significantly influence how individuals assess environmental hazards (Day, 2006; Stoffle and Minnis, 2008; Dąbrowska-Miciula, Bates and Murphy, 2012; Lazrus, 2015). Perceived erosion correlated more with AGB than with visible signs or soil metrics, indicating reliance on tree cover as a key indicator. This suggests local knowledge shapes perceptions more than visible cues or soil conditions, which may lead farmers to underestimate erosion where tree cover is high.

Tree Presence and Soil Aggregate Stability

The results suggest that the soil across the sampled sites has a good level of structural stability, with a healthy dominance of water-stable macroaggregates. The data indicate that soils at the sampled garden are generally in good structural condition, as seen from the high total WSA%. The soil showed a strong presence of stable small aggregates with limited breakdown into microaggregates, a condition often associated with higher carbon content and distinct microbial communities compared to microaggregate-dominated soils (Trivedi *et al.*, 2017). The dominance of WSA-S suggests that the soil is undergoing active aggregation, driven by biological activity and supported by moderate organic inputs (Pulleman *et al.*, 2005; Xu *et al.*, 2021; Vasilchenko *et al.*, 2023) - both are key factors in aggregate formation (Mikha and Wills, 2021). This interpretation is reinforced by the observed correlation between WSA-S and both aboveground AGB (contributing with litter and exudates) and manure application. The lower proportion of large and medium aggregates may point to poor binding agents, disruption in aggregation processes, or disturbance breaking down larger aggregates. As, smaller macroaggregates are more easily detached and transported by water (Rai, Raney and Vanderford, 1954; Abu-Hamdeh, Abo-Qudais and Othman, 2006), they may be carried away by runoff before they have the opportunity to coalesce into larger, more stable aggregates, limiting the progression of the aggregation process and ultimately weakening soil structure over time. Further, although tillage is not commonly practiced in these systems, repeated wetting and drying cycles still occur, which have been shown to physically break down larger soil aggregates into smaller ones—especially in clay-rich soils such as vertisols (Shiel, Adey and Lodder, 1988), which are typical for the Mount Elgon region (Mugagga, Kakembo and Buyinza, 2012b).

Among tree-related variables, tree density was positively correlated with the proportion of WSA-L, suggesting that denser tree stands promote the formation of larger, more stable soil aggregates. Meanwhile, AGB density was positively correlated with the proportion of WSA-S%, indicating that greater AGB may enhance the formation or preservation of smaller macroaggregates. These findings are consistent with qualitative insights from farmer interviews, where soils beneath tree cover were frequently described as being of higher quality. Such perceptions may be grounded in the presence of stable macroaggregates contribute to a well-structured, friable soil matrix less prone to erosion (Bronick and Lal, 2005). Farmers attributed these characteristics to the decomposition of leaf litter and organic inputs, processes known to enhance soil structure and aggregate stability (Abiven, Menasseri and Chenu, 2009; Cao *et al.*, 2020). These patterns are consistent with insights from farmer interviews, where respondents frequently described soils beneath trees as darker, softer, and more fertile. Stable macroaggregates encapsulate organic matter, protecting it from decomposition and thereby enhancing carbon retention, which results in darker soil coloration (black to dark brown)(Stiglitz *et al.*, 2017; Jorge *et al.*, 2021). Hence, soil colour, especially darkness, is used as a practical proxy for SOC (Stiglitz *et al.*, 2017). Increased aggregate stability has been associated with darker soil hues, reflecting higher concentrations of binding agents (Sánchez-Marañón *et al.*, 2004; Sánchez-Marañón, Martín-García and Delgado, 2011). This is further supported, AGB was negatively correlated with perceived soil erosion, meaning that farmers with high AGB reports less severe erosion issues. Besides higher AGB also coincides with increased inputs of organic residues (Cardinael *et al.*, 2018; Prayogo *et al.*, 2021), trees with substantial biomass enhance soil protection via multiple pathways: their canopies intercept raindrops, reducing kinetic energy and subsequent soil displacement; their leaf litter provides ground cover that mitigates splash erosion; and their extensive root systems contribute to soil stabilization (Pimentel and Kounang, 1998). Farmers recognize these biophysical benefits and particularly value tree species that are deciduous, broad-leaved, and have extensive canopies and root systems for their effectiveness in preventing erosion (e.g. *Cordia spp*.)

Tree Species Selection

Cordia spp. showed a significant strong positive correlation with WSA_L% and were frequently mentioned by farmers as effective in preventing erosion and improving soil fertility. These converging findings from interviews, where *Cordia spp.* was emphasized as both ecologically and socially favoured for soil management. *Cordia spp*., particularly *Cordia africana*, are known to enhance soil health in AF systems. Direct evidence linking *Cordia spp.* to improved soil aggregation is limited, but studies in Kenya and Ethiopia reported increased soil moisture, nutrients, organic carbon, and fertility under *C. africana* canopies compared to open fields (Abdella and Nigatu, 2021; Dekeba, Nigatu and Mohammed, 2022; Kamau, Kinyanjui and Kamiri, 2024), with consistent benefits across elevations (Gota *et al.*, 2024). The density of *Eucalyptus spp*. showed a significant positive correlation with WSA%, WSA-M%, and WSA-S%, suggesting that *Eucalyptus spp*. contributes to greater soil stability. Previous studies on *Eucalyptus sp.* cultivation shows mixed effects on soil aggregate stability that vary with soil type, plantation age, and management. Short-term cultivation of *Eucalyptus sp.* does not improve, and may actually limit soil aggregate stability, while prolonged or successive monoculture planting leads to a significant decline in soil aggregate stability, organic carbon, and nutrient stocks, making soils more prone to erosion and degradation (Wang *et al.*, 2021, 2023). In Vertisols, one study reports *that Eucalyptus spp.*

plantations have higher mean weight diameters than cultivated soils (Mohanty *et al.*, 2012). Another study documents 82% aggregate stability in *Eucalyptus sp.* stands compared with 41% in cropland in highland soil (Delelegn *et al.*, 2017). Further studies comparing pure Eucalyptus with mixed-species plantations consistently demonstrate higher aggregate stability in mixed stands (Cui *et al.*, 2023; Zhang *et al.*, 2023). Moreover, several reports note positive correlations between soil organic carbon, organic matter, and aggregate stability (Mohanty *et al.*, 2012; Wang *et al.*, 2021; Cui *et al.*, 2023). While *Eucalyptus spp.* was quantitatively associated with improved soil aggregation in this study, interviews revealed a more mixed perception. Many farmers reported that *Eucalyptus spp.* dries out the soil and negatively impacts crop performance. Nevertheless, some valued the species for its fast growth and commercial benefits, such as timber and firewood production. However, *Eucalyptus spp.* dominates by a large margin, with over three times the number of any other species, likely due to its economic value (fast-growing timber, fuelwood, etc.). *Eucalyptus spp.* is perceived as economically attractive but harmful to soil moisture and crop growth. While there are opportunities to enhance indigenous tree coverage and safeguard natural forests in Mt. Elgon, farmers predominantly cultivate exotic trees, which restricts biodiversity conservation (Graham, Ihli and Gassner, 2022). Youths in Mount Elgon focused on planting economic trees known for their timber, firewood, fruits, and income generation (Galabuzi *et al.*, 2021). *Ficus spp.* was negatively associated with WSA metrics, contradicting the favourable perceptions held by farmers who valued them for their leaf litter and shade. This discrepancy suggests that farmer observations are largely based on surface-level or short-term interactions (e.g., visible leaf mulch or water stress), whereas the ecological impact on soil structure may be more complex or less directly observable. Hence, Farmers may overestimate the benefits of *Ficus spp.* due to observable surface traits (shade, mulch), while underestimating *Eucalyptus'* positive role in soil structure due to its water competition. These findings underscore the need for refining species-specific studies on soil stability, to identify best practices.

Elevation and Soil Structure

This finding is in alignment with several studies indicating that greater elevation was associated with an increased macroaggregate content and larger aggregate sizes. (Wu *et al.*, 2021; Feyissa, Raza and Cheng, 2023; Guo *et al.*, 2025). (Kong *et al.*, 2020) reported that mean weight diameter and geometric mean diameter increased significantly with elevation in alpine forests. Li *et al.* (2016) showed that macroaggregates increased with altitude, while Feyissa et al. (2023) observed that over 49% of large macroaggregates characterised alpine forest and grassland soils at elevations between 2600 and 3900 m. This pattern is often associated with soil carbon stability, enhancing with elevation, and the SOC content in both bulk soils and aggregates tends to increase as elevation rises. SOC is a key factor in soil aggregation and stability. Thus, the higher organic content at greater altitudes can enhance the formation and stability of soil aggregates (Wu *et al.*, 2021; Feyissa, Raza and Cheng, 2023). Other studies noted nuance. (Li *et al.*, 2023) and (Wu *et al.*, 2021) described unimodal patterns with peak stability at mid-elevations. In addition, several papers tied lower temperatures and increased organic carbon at higher altitudes to enhanced stabilization. The farms in this study ranged from 1370 - 1953 m in elevation, which is generally considered to be in the mid-elevation zone as they are still in the lower montane area (Hamilton and Perrott, 1981), thus the finding can potentially be due to cooler temperatures and slower organic matter decomposition with higher elevation.

While statistical analysis points to enhanced soil structure with increasing elevation, in interviews, farmers noted the challenges of erosion in hilly areas, especially during intense rainfall. Several respondents noted that unprotected high-elevation farms were prone to landslides, runoff and erosion. Although the statistical analysis indicates better soil aggregate stability at higher elevations, farmers primarily associated elevation with slope, viewing it as a risk factor for erosion rather than a condition indicative of improved soil structure. Farmer perceptions, however, focus on *slope-related erosion risks* at higher elevations — but they may be referring to farms beyond the mid-elevation range, such as those on steep, exposed ridges or upper hillsides, which could be above the typical range in the study or simply much steeper. Hence, this data supports the idea that topographical variation plays a significant role in soil aggregation and soil structure and that there's a positive association between higher elevation and better soil aggregate stability, at mid-range elevation.

The Gap Between Knowing and Doing

Despite high levels of awareness and generally positive attitudes toward agroforestry (AF), the young farmers assessed in this study—although actively engaged in tree planting—maintain a relatively low on-farm tree density (148,0 ± 129,5 DBH ≥ 5 trees ha^{-1}). For comparison, a study from four forests in eastern Uganda showed a tree density in ranged between 344 and 557 trees ha−1 (DBH ≥ 10 cm) (Eilu, Hafashimana and Kasenene's, 2004). Farmers in this study express deep concern about erosion and demonstrate a clear understanding of the ecological value of trees, particularly in soil conservation and landscape stability. This aligns with previous research, showing that people in Uganda's attitudes toward AF are generally positive (Galabuzi *et al.*, 2021; Bamwesigye *et al.*, 2024, 2024). A 2024 survey revealed that 91% of respondents (age ≤ 45) think AF aids in climate change adaptation, with many emphasizing the role of indigenous trees in this process. However, when asked about Uganda's readiness for agroforestry, responses revealed uncertainty, with many unsure and only a slight majority expressing optimism (Bamwesigye *et al.*, 2024). Many interlocutors in this study voice a desire to increase tree cover on their land. However, awareness and motivation does not translate into practice. (Jerneck and Olsson, 2013, 2014) observed similar patterns in Kenya, describing this phenomenon as the 'adoption gap', which is due to structural barriers that restrict the capacity of farmers—especially the most vulnerable—to act on their aspirations. In the context of this study, key constraints contributing to this gap include land scarcity, food- and economic insecurity—each of which plays a significant role in shaping farmers' decision-making and capacity to invest in AF. From the FGD ranking economic issues and land tenure emerging as the most important and impactful barriers to AF adoption, which aligns with the findings of the qualitative data.

Access and Authority - Generational Tension in Land Tenure

Land-related constraints emerged as significant across both focus groups. "Lack of land" was identified as the second most pressing issue in Focus Group 2 and third in Focus Group 1. Additionally, concerns about "uncertainty over land ownership due to land grabbing" (Focus Group 2) highlight the persistent influence of tenure insecurity on AF decision-making. Interlocutors frequently emphasized that limited access to land poses a significant barrier for fellow youth, primarily due to a lack of financial capital and the reluctance of elders to pass on land to the next generation. Although all interviewed farmers had access to land, whether through ownership or inheritance, this did not necessarily translate into full autonomy over land-use decisions. Traditional land tenure systems remain deeply embedded, with elder family members often retaining control over land decision-making. In line with the findings of this study, research suggests that while younger farmers in east African tend to be more innovative (Kristjanson *et al.*, 2012; Mponji *et al.*, 2024), while other variables like education, farm size, access to credit, and extension services also significantly influence adoption (Fadeyi, Ariyawardana and Aziz, 2022). While youth expressed increasing awareness of the need for climate adaptation strategies - such as agroforestry to avoid erosion and landslides, these approaches are frequently hindered by conservative land tenure structures. In many cases, elders' authority leads to the prioritization of conventional cash crops or short-term economic returns at the expense of more sustainable land-use practices. This conservatism may stem from risk aversion or deeply rooted cultural beliefs, ultimately constraining youth innovation and responsiveness to environmental challenges. These generational dynamics expose an uneven distribution of epistemic authority and land rights, limiting young farmers' ability to implement knowledge-based, adaptive practices within established familial hierarchies. Consequently, generational barriers remain a critical constraint to AF adoption, even when interest and awareness are high. This reveals that phenomena such as landslides, soil erosion, and declining yields are not merely natural occurrences but are socially mediated through access to and control over land. This generational gap means that youth often have the ideas and skills but lack the authority to implement them. In cases where parents still control the land, restrictions are placed on tree planting, discouraging young people from pursuing AF.

Short-Term Survival Strategies

Economic barriers emerged as the most significant challenge to AF adoption, due to their high perceived impact and critical importance. Though not the most cited, financial constraints—such as affording seedlings or land—quickly dominated both FGDs. These findings align with interview data and observations. This may reflect that young farmer, operating in largely subsistence economies, are discouraged by the lack of immediate returns from trees and prefer annual crops that provide quicker income, making long-term investments like AF financially unfeasible for many. This aligns with Ngila (2024), whose study in Kenya found household income to be the strongest determinant of on-farm tree density ($p < 0.001$). Economic pressures contributed to low tree densities, with over half of surveyed farms having fewer than 100 trees per hectare. While AF offers long-term returns and environmental benefits, they require upfront investment, time, and land—resources often scarce among rural youth.

However, the challenge goes beyond initial capital for long-term investments. Participants also cited delayed returns from tree planting as a concern. Many prefer fast-yielding crops to meet immediate needs, and some cut down trees to cover expenses like school fees or food. Perceptions that trees will compete with food crops (for sustenance or cash) for space, light, and nutrients often discourages AF adoption. On small plots, concerns about reduced yields of staples like beans, maize, and bananas are common. While many recognize the long-term benefits of trees, immediate income from food crops is essential for survival and thus short term economic- and food security are prioritized. This reinforces Jerneck and Olsson's (2013, 2014) concept of the "food imperative" as a dominant logic in smallholder decision-making. They argue that for many farmers, especially those in vulnerable conditions, the need to secure daily food and income overrides long-term investments. The empirical data affirms this risk aversive behaviour dominating decisions making. For many, the opportunity cost of tree planting is too high when returns are slow and immediate needs are pressing. The opportunity cost of tree planting remains too high for many to overcome, creating a gap between knowledge/willingness, and action. This points to a fundamental tension:

while sharing the same space, soil and farmer operate on different temporalities. Whereas farmers must often prioritize immediate yields and short-term survival, soil restoration and degradation processes unfold on ecological or planetary timescales.

Young farmers have a highly localised understanding of soil, focusing on practical experiences rather than abstract theories or concepts, reflecting their modes of knowledge formation. They primarily focused on soil as a medium for agriculture, whether for subsistence or sale. Farmers consistently emphasized that the primary value of erosion control is trees' role in preserving soil fertility to support productive crops. Some farmers, particularly those involved in extension trainings, expressed concerns about landslides from deforestation and reluctance to adopt tree planting, seeing soil as essential not just for cultivation but also for landscape stability. Similarly, Bamwesigye *et al.* (2024b, 2024b) found that youth engage in AF mainly for nature preservation, soil conservation, water regulation, and economic benefits, with climate change being a lesser concern. Although some farmers recognise the value of soil and tree cover, for broader environmental concerns like global warming and carbon sequestration, this rarely influence their decisions, as immediate, tangible outcomes of AF take priority, consistent with findings by De Giusti, Kristjanson and Rufino (2019) in rural western Kenya. While international policies often emphasize agroforestry as a tool for climate change mitigation, young farmers tend to prioritize more immediate and tangible benefits. Their practical concerns are rooted in their day-to-day experiences and inherited knowledge. As a result, they may find it difficult to connect with broader narratives around environmental adaptation, which can seem disconnected from their lived realities. This illustrates what Jerneck and Olsson (2014) term *ontological stratification* - the gap between abstract planetary/global solutions and the lived realities of smallholder farmers. This disconnect hinders agroforestry adoption by promoting visions misaligned with farmers' survival-driven priorities and local practices.

Security Dilemmas

While rural youth recognize the ecological and agronomic benefits of shade trees in coffee AF systems, such as improved soil quality, enhanced *C. arabica* yield and coffee quality, microclimate regulation, and erosion control, their integration into smallholder farms presents critical trade-offs. These trade-offs constitute a significant *security dilemma* for young farmers, who often manage or inherit limited land and must simultaneously meet household food needs and generate income. Farmers report that shade trees, though valuable for coffee production, may not be compatible with the cultivation of staple subsistence crops like *Musa* spp., *Z. mays*, and various annual vegetables, which require full sunlight for optimal yields. On small plots, the spatial and biophysical requirements of AF directly compete with those of food crops, creating a zero-sum situation. Shade in AF systems has complex effects on crop productivity. While shade provides soil health benefits such as improved microclimate, drought resistance, and pest control, it can reduce yields by limiting light availability (Dufour *et al.*, 2013; Ivezić, Yu and Werf, 2021). For *C. arabica* moderate shade (20-40%) can enhance growth and coffee quality without significantly reducing yields (Vaast *et al.*, 2006; Haggar *et al.*, 2021), as light-use efficiency increases in shaded coffee plants, partially compensating for reduced radiation (Charbonnier *et al.*, 2017). *Musa* spp. is shade tolerant to some extend, with photosynthesis and growth acclimating to natural shade in the humid tropics (Senevirathna, Stirling and Rodrigo, 2008). However, *Musa* spp. show a linear decrease in yield and photosynthesis with decreasing light levels (Israeli *et al.*, 1996). Other crops like *Z. mays*, which is a C4 plant, requires high light intensity. Heavy shade (50%) significantly reduces maize biomass and grain yields (Schulz *et al.*, 2018; Gao *et al.*, 2020). Increased shading necessary for optimal coffee production can thus reduce the productivity of these food crops, thereby undermining short-term household food security.

Despite the promise of coffee AF as a sustainable and climate-resilient livelihood strategy, many young people face a strategic crossroads: whether to invest in long-term ecological and income benefits or to prioritize immediate food production needs. This tension is particularly acute on smallholdings, where planting shade trees often displaces food crops, leaving little space or sunlight for their cultivation. In such cases, families may become increasingly dependent on market purchases for food, exposing them to price volatility and deepening economic vulnerability. All gardens are very small, and well within the smallholder category, typically defined as farms under 2 hectares in many global and regional classifications (Lowder, Skoet and Raney, 2016). The findings from this study show that larger garden sizes are significantly correlated with both higher tree biomass density and overall tree density. This suggests that land size acts as a critical enabling factor for AF adoption. This aligns with the findings of Galabuzi *et al.* (2021), who found that land size had a positive significant effect on integration of tree and land scarcity was the most important hindering factor among youths. This indicate that youth with access to larger plots are better able to balance the competing demands of income generation through shaded coffee production and the cultivation of food crops. In contrast, those with smaller landholdings face sharper trade-offs, as the introduction of shade trees can directly displace essential food production. Drawing on Jerneck and Olsson's (2014) conceptualization of the "food imperative," this dilemma illustrates the structural constraints faced by risk-averse smallholders, who prioritize daily caloric intake and labor-efficient strategies over long-horizon investments like AF. While youth may support AF for its environmental and market potential, their limited landholdings and pressing subsistence needs often render such practices too risky. As a result, many opt to limit or forego full adoption of AF systems, not due to lack of interest, but because of the inherent trade-offs between long-term environmental goals and short-term food security imperatives. This aligns with Kristjanson *et al.* (2012), who found that food security status correlates with innovation, with food-insecure households less likely to adopt new practices. In response, some youth seek to resolve this dilemma by acquiring additional land exclusively for food production, thereby preserving *C. arabica* yield while addressing subsistence needs. While this strategy can improve household food security without sacrificing economic security, this dual-land strategy can drive unintended consequences as it will also increase overall land consumption. In Mount Elgon, where land is scarce, food plots are often pushed into marginal, steeper or erosion-prone areas. Some entail expanding cultivation further up the mountain, potentially encroaching on primary forests. If primary forests are cleared to make room for subsistence plots displaced by shaded coffee areas, AF may inadvertently contribute to accelerating deforestation and land degradation. This paradox challenges the notion that such systems are inherently sustainable. This support Jerneck and Olsson's (2014)s caution, the apparent sustainability of AF must be critically examined within the socioecological context of land pressure, market dependence, and systemic risk aversion among smallholders. Thus, AF initiatives targeting youth must move beyond the biophysical and economic rationale for tree planting and engage with the structural socioecological realities of rural livelihoods. Without such holistic planning, well-intentioned AF projects may inadvertently incentivize forest clearing, undermine biodiversity, and entrench rather than alleviate rural vulnerability.

CONCLUSION AND PERSPECTIVES

Young small-scale coffee farmers in Mount Elgon understand tree–soil relationships mainly through direct, embodied experience, hybridized with formal knowledge and local epistemologies. Youth consistently perceive trees as essential for improving soil quality, retaining moisture, and reducing erosion - insights that are partially supported by biophysical data, particularly the positive associations between tree density, biomass, and soil aggregate stability. Yet, not all farmer perceptions, biophysical evidence and scientific literature, align. This highlights the need for context-specific research to identify species and AF systems that effectively balance ecological function and farmer priorities.

In rural areas like Mount Elgon, where formal soil testing is inaccessible, local epistemologies and visible surface cues, rather than subsurface indicators of soil structure, are commonly used to assess soil quality and guide land stewardship. These lived insights are not only coherent but often aligned with biophysical data. Since many farmers learn visually, extension work should train farmers to recognize indirect signs of soil structure, hands-on or visual tools can help bridge scientific ideas with practical observation. Integrating local knowledge with scientific expertise improves environmental decision-making and risk management, especially in rural areas (Corburn, 2003; Friendship & Furgal, 2012). These local indicators may offer simple, effective and context-specific tools for evaluating soil health. However, larger or longitudinal studies are needed to determine whether such perceptions align with biophysical realities. Participatory approaches that incorporate farmers' erosion indicators are essential to understanding local epistemologies.

Yet, knowledge does not automatically lead to action. Youth are often constrained by limited land access, poverty, and intergenerational authority over land-use decisions. As such, agroforestry adoption is shaped not only by knowledge (whether scientific or phenomenological) or by attitudes. The bottleneck, however, lies in the material and relational conditions that structure young farmers' agency and ability to balance short-term needs with long-term goals. Moving forward, interventions or future research must address these structural constraints and dilemmas to enable meaningful engagement. Future work should also identify shade-tolerant crops and develop agroforestry models that meet short-term economic and subsistence needs, to prevent increased land consumption and avert potential deforestation. Farmers lived knowledge of specific species offers a valuable foundation for interdisciplinary research to identify species that enhance both soil quality and productivity, while being culturally appropriate. Finally, enhanced youth empowerment and/or community dialogues are needed to mediate intergenerational land-use conflicts and build shared commitments to sustainable practice.

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PART 2: THESIS REPORT

SUMMARY

This thesis provides the theoretical and methodological foundation for the thesis product: a manuscript exploring the reciprocal relationships between soils and young farmers. It examines the increasingly complex entanglements between ecological and social systems in the Anthropocene, a geological epoch characterised by the unprecedented scale and pace of human-driven changes to Earth's climate, landscapes, and biological systems. As climate change and land degradation intensify, they create feedback loops that destabilise ecosystems, livelihoods, and socio-political systems, demanding a fundamental rethinking of environmental stewardship, science, and agriculture.

The thesis traces the philosophical roots of the human–nature divide, illustrating how Western thought, from early philosophical traditions to the Modernist 'great divide,' has progressively separated humans from the natural world, profoundly shaping the evolution of the scientific paradigm. Contemporary currents in environmental philosophy—including feminist theory, posthumanism, and new materialism—challenge this separation. They question the centrality of the human subject, critique hierarchical dualisms, propose more distributed and decentred models of agency, and emphasize relationality and situated knowledge. These approaches further disrupt traditional binaries by attributing agency to matter itself. Bruno Latour's Actor-Network Theory (ANT) dissolves the boundary between human and non-human entities, offering a relational ontology in which agency is distributed among networks of actors shaping ecological and social realities.

In the Anthropocene, the emergence of superwicked problems and the challenge of stewarding hyperobjects reveal the inadequacy of traditional models of environmental stewardship. This thesis advocates for rethinking stewardship through frameworks that recognise the interdependence of human and non-human life within the planetary context that the Anthropocene necessitates. More-than-human stewardship emphasises ethical, reciprocal relationships between humans and other species, while planetary stewardship calls for responsibility on a global and planetary scale, in addressing the complex, interconnected crises we face.

Within this theoretical context, the thesis turns to agroecology (AE) as a model for sustainable agriculture and environmental stewardship. AE, as an integrative approach combining ecological science, social movements, and local farming practices, has the potential to serve as a transdisciplinary framework capable of addressing the multiple human security challenges related to the ecological crises of the Anthropocene. However, despite its transdisciplinary aspirations, AE research often remains predominantly rooted in the natural sciences and insufficiently incorporates insights from the social sciences, traditional ecological knowledge, and indigenous epistemologies. This disciplinary narrowness limits AE's ability to fully address the socioecological complexities of the Anthropocene. The thesis argues that for AE to respond effectively to global environmental and social challenges, it must move beyond merely claiming a holistic and interdisciplinary stance and truly become a transdisciplinary science. It must integrate diverse disciplinary perspectives, embrace a plurality of knowledge systems, and scale its focus from local agroecosystems to global food systems, recognizing the planetary boundaries within which agriculture must operate. Ultimately, the thesis contends that the concept

of the Anthropocene exerts an epistemological and ontological pressure on scientific disciplines surrounding AE. These pressures demand a convergence of ecological and social sciences into new hybrid forms of inquiry.

The thesis presents the case of agroforestry (AF) as an AE soil management practice that integrates trees and crops within farming systems. It reviews current research on AF's effects on soil organic matter, structure, and water retention, highlighting how it supports soil ecosystems and builds resilience to climate variability. AF exemplifies the principles of ecological sustainability and social resilience that are entangled within AE systems. It not only restores degraded landscapes but also supports human security by bolstering the livelihoods and food security of farming communities, particularly in vulnerable regions. Building on the theoretical frameworks presented, the thesis details the methodological approach employed in the product article. It combines Grounded Theory, ANT, and socioecological systems thinking within a mixed-methods approach to ethnopedology. This product exemplifies a scientific work that bridges natural and social science traditions to study human-soil relationships.

Characters (with spaces): 95.829

ABBREVIATIONS

AE	Agroecology / agroecological
AF	Agroforestry
AFS	Agroforestry system
AFSA	Alliance for Food Sovereignty in Africa
AMF	Arbuscular Mycorrhizal Fungi
ANT	Actor-Network Theory
CH_4	Methane
CO_2	Carbon Dioxide
FAO	Food and Agriculture Organization (of the United Nations)
GHG	Greenhouse Gas
GT	Grounded Theory
HS	Human Security
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
N_2O	Nitrous Oxide
N	Nitrogen
NH_4^+	Ammonium
P	Phosphorus
PSB	Phosphate-Solubilizing Bacteria
PSF	Phosphate-Solubilizing Fungi
SES	Socioecological System
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
UBOS	Uganda Bureau of Statistics
UNDP	United Nations Development Programme

1. INTRODUCTION

At the foothills of Masaba, also known as Mount Elgon, where mist drapes the steep slopes in the morning, farmers tread the narrow paths between small plots of land. Their rubber boots sink into the mud, thick and slippery from the season's heavy rains, as a heavy bunch of matooke balances effortlessly on their head. For generations, the Sabei and Bugishu peoples have depended on this land, cultivating its slopes for food and income, and the rich, volcanic soils of Masaba have sustained their crops. But now, the soil tells a different story. Where forests once grew, and banana plantations flourished, scars now mark the mountainsides - remnants of erosion and landslides that swallowed lives, homes and livelihoods in an instant. This is not just one farmer's struggle, nor a single village's fate. It is the reality for millions across the world, as anthropogenic climate change and land degradation intertwine to reshape entire ecosystems, exerting cascading effects on Earth system stability (Eswaran, Lal and Reich, 2019; IPCC, 2023). Globally, land degradation is a significant environmental challenge driven by various natural and human-induced factors. According to The Food and Agriculture Organisation under the United Nations (FAO) and The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), about one-third of the Earth's land is moderately to highly degraded, negatively affecting 3.2 billion people. Further, global soil erosion rates are much higher than soil formation rates. Thus, over 90% could become degraded by 2050. Forty per cent of these degraded soils are situated in Africa, with the majority found in areas experiencing significant poverty and food insecurity (FAO and ITPS, 2015; IPBES, 2018). Soil degradation is caused by soil erosion (e.g., water erosion, wind erosion), chemical deterioration (e.g., salinisation, nutrient depletion) and physical degradation (e.g. soil compaction, loss of soil structure). These effects can be intensified by human activities such as improper agricultural practices (e.g., excessive tilling, monocropping), overgrazing (e.g., livestock overstocking), deforestation and land use change (e.g. clearing forests for agriculture or urban development) (Bridges. and Oldeman, 1999; Jie *et al.*, 2002; Smiraglia *et al.*, 2016). Soil erosion is a major cause of land degradation, particularly in Sub-Saharan Africa, where intense rainfall, poor soil structure, and steep slopes exacerbate the problem (Kiage, 2013).

Climate change and land degradation are interconnected processes that exacerbate each other. Anthropogenic climate change drives land degradation by altering temperature, wind, and precipitation, reducing soil moisture, plant biomass, and land cover. This accelerates soil erosion, depletes soil organic carbon (SOC), and lowers agricultural productivity. (Webb *et al.*, 2017; Talukder *et al.*, 2021; Roy *et al.*, 2022; Stavi, Priori and Thevs, 2022). Meanwhile, land degradation exacerbates climate change by releasing carbon from soil and vegetation, boosting greenhouse gas (GHG) emissions. This creates a feedback loop that further intensifies climate impacts (Roy *et al.*, 2022). Soil is a self-organising, emergent system that supports plant and microbial growth and enables the functioning of the Earth system. Land degradation typically results in a reduction of ecosystem services, impacting both ecological and social systems (Smiraglia *et al.*, 2016; Sharafatmandrad and Khosravi Mashizi, 2021), which affects human well-being and increases human and non-human vulnerability to climate change (Smiraglia *et al.*, 2016; Webb *et al.*, 2017; Prăvălie *et al.*, 2021; Stavi, Priori and Thevs, 2022). The combined effects of climate change and land degradation lead to food and nutritional insecurity, health issues, economic insecurities, and increased migration and conflict, particularly in vulnerable regions (Hermans and McLeman, 2021; Mani, Osborne and Cleaver, 2021; Talukder *et al.*, 2021). Hence, the interplay between climate change and land degradation forms what could be called *entangled ecologies*[1] of environmental decline and socio-economic vulnerability, emblematic of the Anthropocene—an era defined by human impact on Earth's geology and ecosystems (Crutzen, Steffen and Stoermer, 2000; Crutzen, 2002).

In this thesis report, I argue that the Anthropocene context exerts a force that pulls the scientific disciplines surrounding environmental stewardship and agriculture closer together, as their systems get increasingly entangled. Additionally, I contend that while agroecology (AE) positions itself as a transdisciplinary scientific field, it largely remains confined within its traditional boundaries and struggles to fully integrate social and environmental sciences to effectively address the challenges of the Anthropocene. In light of this analysis, I present my thesis product - a manuscript for a journal article on the reciprocal relationships between mountainous soils and young farmers. The article manuscript is an AE case study that aims to bridge the methods traditionally used in the social sciences with those of the natural sciences in understanding human-soil relationships. This thesis report constitutes the second part of my overall thesis. The first part is presented as an article manuscript, which should be read first. This report serves as a complementary component, expanding on key themes and providing a broader theoretical framework as well as the methodological considerations surrounding the process of its creation. Together, these two parts form a comprehensive thesis.

3. THEORETICAL FRAMEWORKS

3.1 The Anthropocene

Human activity is transforming the planet, linking local environments to global biogeochemical cycles and geophysical processes. The unprecedented rate, scale, nature, and complexity of these changes distinguish this era from any in history (Evrendilek, 2012; Huggett, 2018). As landscapes transform and the climate shifts, it becomes increasingly clear that humanity has become a driving force in Earth's ecological and geological systems (Zalasiewicz *et al.*, 2008; Lewis and Maslin, 2015; Waters *et al.*, 2016). Human societies and globally interconnected economies are reliant on ecosystem services and functioning (Pharo and Daily, 1998; Gomez-Baggethun and Groot, 2010). The complex web of interdependencies between natural and social processes, unfolding across various temporal and spatial scales, necessitates a suitable conceptual framework. This led the atmospheric chemist Paul Crutzen (2000) to introduce the term *Anthropocene,* proposing that we have entered a new geological epoch characterised by human-driven changes to Earth's systems on a planetary scale (Steffen, 2021). The term has received increasing acceptance, and the concept has now been shaped and discussed by multiple scholars. The Anthropocene is defined by human activity becoming a geological force, capable of transforming Earth's climate, biodiversity, and sediment layers (Waters *et al.*, 2016; Waters and Turner, 2022). Phenomena characterising this epoch include: 1) The presence of new materials that did not exist in previous epochs. These include synthetic materials such as plastics, concrete, and industrial chemicals, which are now widespread and have the potential to persist in the geological record as *technofossils*[2] (Zalasiewicz *et al.*, 2014). 2) Human-driven alterations in biogeochemical cycles have caused unprecedented increases in carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)

[1] *Entangled ecologies* refer to the dynamic, interdependent relationships between human and non-human systems, including biological, social, and technological processes that co-shape one another across time and space.
[2] *Technofossil* refers to a human-manufactured material or artefact with sufficient durability to be preserved in the geological record, serving as evidence of anthropogenic influence on Earth's stratigraphy.

concentrations, disrupting the atmosphere's composition (Waters et al., 2016). Soil nitrogen (N) and phosphorus (P) levels have doubled in the past century due to extensive fertiliser use, while industrial pollutants have become widespread (Smith, McDonald and Patterson, 2020). Anthropogenic climate change, driven by increased GHG emissions due to industrialisation, fossil fuel combustion and deforestation, has resulted in global temperatures rising beyond natural Holocene[3] variations (Ruddiman *et al.*, 2016; Waters *et al.*, 2016). This warming has led to accelerated glacier retreat, rising sea levels (Nerem *et al.*, 2018; Zemp *et al.*, 2019), changing weather patterns, more extreme weather events and disruptions to ecosystems (Diffenbaugh *et al.*, 2017; IPCC, 2023). 3) Biological transformations of biomass through biological annihilation[4] due to accelerated species extinction rates surpassing background levels - often referred to as the *Sixth Mass Extinction* (Pievani, 2014; Cowie, Bouchet and Fontaine, 2022). Anthropogenic alteration of the Earth's surface because of widespread land-use change, the spread of invasive species due to globalisation, as well as pollution and waste accumulation, has brought habitat destruction (Pievani, 2014; Ceballos, Ehrlich and Dirzo, 2017). While the exact onset of this epoch remains contested, these combined indicators establish that the Anthropocene is both functionally and stratigraphically distinct from the Holocene (Waters *et al.*, 2016)

3.1.1 From Harmony to Hegemony: The Philosophical Roots of the Human–Nature Divide

While many pre-modern and indigenous worldviews saw humans as part of a unified cosmic order (Kimmerer, 2013), the conceptual divide between humans and nature has deep philosophical roots. Plato and Aristotle framed humanity and nature as a hierarchical yet non-antagonistic dualism, viewing humans as part of nature but distinct through reason (*logos*) (Moss, 2014). Stoicism viewed nature as permeated by divine reason (*logos*), advocating for a life in accordance with nature—a view echoed in modern ecological ethics (Long, 2010). Aristotle's *De Anima* ranks souls hierarchically—plants have nutritive, animals sensitive, and humans rational souls (Aristotle, 350AD) - establishing human exceptionalism and used to justify dominance over other life forms in the *scala naturae* (great chain of being) (Lovejoy and J. Stanlis, 2017). In Judeo-Christian tradition (Genesis 1:28, *The Holy Bible.*, 2011) grants humans dominion over nature, a concept interpreted as both stewardship and exploitation (White, 1967). Scholars like Lynn White, argue that this view shaped Western attitudes, contributing to environmental degradation (White, 1967). This anthropocentric legacy was reinforced during the Enlightenment, which emphasised reason, science, and progress, redefining nature as separate from human society (Descola and Sahlins, 2014). René Descartes' dualism is emblematic of this shift exemplifies this shift, drawing a clear line between *res extensa* (matter) and *res cogitans* (mind) (Mazzocchi, 2016; Sullivan, 2016). In this view, nature became a lifeless, mechanistic object—devoid of meaning or agency—and open to human control, while culture and reason were elevated as uniquely human traits (Vaccari, 2012; Lescura, 2021). Francis Bacon advanced the empirical method, viewing scientific knowledge as a way to harness nature for human benefit, while depicting nature as passive and knowable only through human intervention (Feitosa *et al.*, 2024). John Locke saw the mind as a blank slate shaped by experience, grounding knowledge in culture rather than nature. His labor theory of property claimed human effort gives nature value, justifying its transformation into economic

[3] The most recent interglacial epoch of the Quaternary Period spans about the last 11.700 years of Earth's history (Walker *et al.*, 2019).

[4] The rapid and widespread extinction and decline of populations across numerous species, significantly reducing biodiversity and signalling an acceleration toward mass extinction (Ceballos, Ehrlich and Dirzo, 2017).

resources (Kolia, 2015). G.W.F. Hegel saw nature as an unconscious stage in Spirit's self-realization, with true freedom and self-consciousness emerging only through culture—language, history, and philosophy—placing nature on a lower ontological level. (Furlotte, 2018; Schuelein, 2021). At the advent of modernity, Western European philosophy had articulated a conception of a culture–nature divide, separating the realms of culture and nature into ontologically autonomous domains. This *great divide* became a defining feature of Western modernity (Descola and Sahlins, 2014; Mathieu, 2022). During the colonial era, Western powers imposed their cultural, educational, and religious frameworks on colonised regions, marginalising indigenous philosophies and ecological understandings in favour of anthropocentric views (Cronon, 1996; Mahanty, S., 2007). Globalisation has further disseminated these Western ideas, integrating them into science and curricula, sidelining local ecological knowledge worldwide (Gadgil, Madhav, Berkes, Fikret, and Folke, Carl, 1993; Berkes, Colding and Folke, 2000; Verma *et al.*, 2016). Additionally, Western literature, media and capitalist models have reinforced a narrative of human separation from and superiority to nature, promoting resource exploitation and environmental degradation (Cronon, 1996; Martinez-Alier, 2014). This global spread of Western anthropocentrism has not only justified extensive resource use, leading to crises such as deforestation and pollution, but also eroded indigenous ecological wisdom (Berkes, Colding and Folke, 2000; Martinez-Alier, 2014).

3.1.2 Dissolving Human-Nature boundaries

Contemporary scholars across several critical schools of thought, including feminist theory, posthumanism, and new materialism have challenged the notion of the human-nature divide. {Citation}Timothy Morton (2016) critiques the conventional notion of nature as a pristine, external entity separate from humans. They argue this view fosters a false detachment, leading to environmental degradation and misunderstanding of our ecological entanglements with non-human entities. Morton encourages recognizing this entanglement, viewing humans as integral to the ecological *mesh*, where all entities are interconnected and interdependent. Morton argues that traditional environmentalism often reinforces the human-nature divide by idealizing nature as something "out there," separate from us. Instead, they suggest that recognising the inherent interconnectedness can lead to a more authentic ecological awareness. By introducing the concept of *dark ecology,* Morton suggests that understanding our place in the ecological mesh involves confronting the "irony, ugliness, and horror" in ecological realities, which disrupts romanticised views of nature and prompts more genuine engagement with the environment that acknowledges both its beauty and darkness (Morton, 2016). Bruno Latour (2007) contends that the nature-culture dichotomy is a construct of modern Western thought, failing to reflect our intertwined reality. He believes nature and culture are inseparable and continuously co-construct each other. This aligns with Donna Haraway's concept of *naturecultures*, emphasising the inseparability of what we often label as "natural" and "cultural". They argue that humans and non-humans co-construct each other through intertwined relationships, continuously shaping and define each other continuously, and should thus be considered together. (Haraway, 2008, 2012).

Latour's

We Have Never Been Modern (1991) offers a critical re-examination of the foundational assumptions of modernity, particularly the perceived dichotomy between nature and society. At the heart of Latour's argument is the concept of the modern constitution, a conceptual framework that underpins modern Western thought. This constitution enforces a strict epistemological and ontological separation between the domains of nature, governed by objective scientific laws, and society, shaped by subjective human affairs. According to Latour, this binary has structured scientific practice, political discourse, and institutional organisation throughout the modern era. Purification, in Latour's terms, is the modern process of artificially separating nature and society into distinct, independent domains. Latour challenges this foundational separation by highlighting the existence of hybrids—entities that combine elements traditionally viewed as belonging to either the natural or social realms, thereby blurring or collapsing the distinction between them. These include phenomena such as climate change, genetically modified organisms, and digital technologies, all of which emerge from intricate entanglements of human structures. Such hybrids, or what Latour calls quasi-objects, defy the dualistic logic of modernity and exemplify the need for a more integrated framework of analysis. Latour's central provocation is that "we have never been modern." By this, he does not imply a return to premodern cosmologies, but rather suggests that the modern project, as traditionally conceived, has always been internally inconsistent. The separation of nature and society is not a discovery of modern reason, but a discursive strategy that conceals the work of hybridisation that has always characterised human-nonhuman relations (Latour, 1991). As such, Latour calls for a reassembling of the social—a methodological approach that traces the associations between actors of all kinds, without presupposing categorical distinctions between them (Latour, 2005)

3.1.3 Actor-Network Theory

Actor-Network Theory (ANT) is a framework for analysing the formation and maintenance of networks of relations among diverse entities, developed primarily by Bruno Latour, Michel Callon, and John Law in the 1980s, as a response to the limitations of traditional sociology and its anthropocentric focus. By proposing a symmetric and heterogeneous approach to social analysis, ANT asserts that non-human entities such as technologies, artefacts, and texts are as crucial as human actors in shaping outcomes (Latour, 2005). ANT reconceptualises the notion of *agency*[5] by introducing the concept of the *actant*, which encompasses both human and non-human entities. In classical philosophy and much of modern science, a clear boundary exists between the *subject* (typically the human observer or agent) and the *object* (the thing being observed or acted upon). Latour challenges this division by proposing that subjects and objects are not foundational categories but are instead outcomes of relational networks. They are defined not by inherent properties but by the positions they occupy within a web of associations. According to Callon (1984), any entity that modifies a state of affairs by making a difference can be considered an actor. In a semiotic sense, an actor is any element that acts or to which activity is granted by others. Hence, the actor-networks are *heterogeneous* – an actant can be human (e.g. farmer, scientist, extension worker) or non-human (e.g. trees, soil microbes), and it can be material (e.g. sediment, money, tools) or immaterial (e.g. knowledge, acquaintances, market trends). The intention is not to anthropomorphise inanimate objects or non-sentient beings, but to acknowledge the specific role they play in co-constructing the actor-network. Actors are not necessarily intentional, as agency in ANT does not require consciousness or deliberate purpose but is instead defined by the capacity to produce effects within a network. It gains its identity through its relations and interactions within the network. These actors are embedded in *actor-networks*, which are temporary and dynamic associations that collectively produce effects (Latour, 2005). Importantly, within ANT, networks are not already

[5] The capacity of individuals or entities to act and intervene in the world and exert influence over their environment or circumstances (Giddens, 1986).

traced out or predetermined structures, on which actants operate. Rather, they are emergent and contingent assemblages that must be empirically traced through the practices, connections, and negotiations of the actants themselves - it is what emerges from the associations that actors themselves build. Hence, the *actor-network* is a constant process of making and remaking relations, and the interactions between actants need to be constantly performed (Law, 1992). The restructuring and coordination of relationships are facilitated through a process known as *translation*. Translation refers to the mechanisms through which actors define roles, negotiate relationships, and enrol others into their networks. This is how connections between actants are built and maintained. Callon (1984) outlines four moments of translation: *problematization, interessement, enrolment*, and *mobilization.* Problematization occurs when a central actor defines a problem and positions itself as essential to the solution. In interessement, this actor tries to convince others to accept the roles proposed to them. Enrolment follows, where actors agree to these roles and a network begins to form. Finally, mobilization ensures that representatives speak and act on behalf of the network, stabilizing it and allowing coordinated action. A key feature of ANT is its commitment to a *flat ontology*[6], where human and nonhuman actors are treated equally. The principle of *generalized symmetry* rejects the assumption that only humans have agency; objects, technologies, texts, and animals can also shape outcomes and relationships (Callon, 1984). Hence, ANT reconfigures the traditional boundaries between the social and ecological by treating both human and non-human entities as equally significant in the construction of reality. This means that all actors, regardless of their nature, are treated equally in the analysis. ANT rejects distinctions such as social vs. natural, arguing instead for a focus on *associations* and *relations*. (Law, 1992) emphasises that reality is enacted through practices and that the analyst must follow the actors themselves to understand how networks are built and maintained.

3.1.4 Spatio-Temporal Implications of the Anthropocene

Traditionally, human history has been understood on a short timescale - centuries, millennia, or, at most, the rise and fall of civilisations. The Anthropocene introduces a deep time perspective, forcing us to think in geological rather than human timescales and reckon with Earth's vast planetary history spanning millions to billions of years. In *The Climate of History in a Planetary Age* by Dipesh Chakrabarty (2021) distinguishes between the *global* and the *planetary*, arguing that the Anthropocene, especially climate change, compels us to rethink history beyond anthropocentric time perspectives. The Anthropocene challenges traditional historical thinking by revealing humans not only as agents within global economies, politics, and cultures, but also as geological forces reshaping the planet. The Anthropocene is defined by *superwicked problems* - complex, urgent issues that are extremely difficult to solve (Rittel and Webber, 1973; Levin *et al.*, 2012). As conceptualised by Levin *et al.* (2012), they have four key characteristics. First, time is running out - the longer we wait to address the issue, the harder it becomes to resolve. Second, there is no central authority or singular governing body that can enforce a solution. Third, the very actors trying to solve the problem are also causing it - e.g. governments, corporations, and individuals who work to address climate change are also contributing to it through carbon emissions and resource consumption. Finally, policies often irrationally discount the future, prioritising immediate economic and political concerns at the expense of long-term

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[6]A philosophical position that denies any fundamental hierarchy among entities - humans, animals, objects, and inanimate objects - possesses equal ontological status. It rejects hierarchical distinctions, as no entity is assumed to be more real, important, or foundational than another (DeLanda, 2006).

sustainability. The concept of *hyperobjects*, introduced by Timothy Morton (2013), describes entities so vast in scale and temporality that they exceed human comprehension. Examples include climate change, nuclear waste, and global capital systems—phenomena that are distributed across time and space in ways that make them difficult to grasp directly. Firstly, hyperobjects are characterised by their viscosity. They stick to everything and cannot be easily separated from daily life. Secondly, they are characterised by their non-locality, meaning that their effects are everywhere, but they are not reducible to a single location. Lastly, they are defined by their temporal undulation. They operate on timescales that far exceed human lifespans, making their full impact hard to perceive.

Soil serves as an illustration of a hyperobject. Firstly, it is massively distributed in space and time, as it extends across the entire surface of the Earth, and its formation spans both global and planetary scales. Humans interact directly with soil at localised scales (farms, gardens, construction sites), but comprehending soil globally, including all its varieties, microbial communities, nutrient cycling, and geological histories, is beyond direct human experience. Soil systems exhibit a range of properties, including microbiomes (Margerison, Nicolitch and Zhang, 2020), cultural identity, (Kala, 2013; Wells and Antonucci, 2018), fertility (Grant, 2017), spirituality (Pigott, 2021), carbon sequestration (Nair, Mehta and Sharma, 2015)and political significance (Huber, 2019; Hokkanen, 2024), that emerge from countless interconnected interactions. These interactions - biological, chemical, physical, social, cultural, and political - operate simultaneously across multiple scales. Soil health has profound significance, fundamentally determining the health of ecosystems, agriculture, climate stability, and biodiversity (Lal, 2001; Eswaran, Lal and Reich, 2019). Soil degradation occurs simultaneously worldwide, transcending local, regional, and national boundaries, and its consequences extend far beyond local, immediate, and visible signs of erosion or reduced fertility. Practices such as agriculture, deforestation, and pollution in one region can indirectly impact distant ecosystems by disrupting biodiversity and global carbon cycles (Karlen and Rice, 2015; Kraamwinkel *et al.*, 2021). Thus, changes in soil processes have enormous and cascading local, global and planetary implications (Kraamwinkel *et al.*, 2021). Further, the enormous time lags between cause and effect significantly complicate our ability to recognise, measure, and respond effectively to soil degradation (Syers, 1997; Sparovek and Schnug, 2001). These delays mean the full consequences of degrading soil health often remain hidden for decades or centuries, exceeding the global timescales within which political and societal systems typically operate. The vast, gradual and cumulative nature of soil degradation makes it challenging to recognise fully from any single vantage point in space or time, often rendering it subtle to immediate human perception. Soil's hyperobject nature makes degradation not just complex but superwicked, characterised by intricate feedback loops, spatial and temporal disjunctions, and profound uncertainty. Additionally, because soil degradation involves interlinked ecological, economic, political and social dimensions, it necessitates coordination among countless stakeholders with conflicting interests, values, and perceptions of urgency (Louwagie *et al.*, 2011; Kapović Solomun *et al.*, 2021; Mekuria *et al.*, 2021), ultimately undermining the prospects for timely and effective intervention. These entangled relationships also make soil degradation inseparable from other hyperobjects, such as global economics (Puskar, 2017) or climate change (Morton, 2013) - forming what could be called a *hyperobject-web* of cause-and-effect that defies easy simplification or solution.

Table 1
Comparison between traditional/modernist environmentalism and post-human environmentalism

Modernist naturalism	**Post-human environmentalism**
Anthropocentric Humans are the primary actors and stewards of nature.	Post-anthropocentric Humans are one actor among many in ecological systems.
Nature/culture divide Assumes a separation between humans and nature.	Nature-culture entanglement Humans, nonhumans, and technology are interconnected.
Conservation and protection Focuses on preserving "pristine" nature.	Co-becoming and symbiosis Acknowledges hybrid ecosystems (e.g., urban nature, rewilding) and dynamic transformation as natural states.
Environmental Policy-Centric Solutions often come from governmental and institutional policies. Nature is a passive object	Distributed Agency Solutions involve collaboration between humans, animals, machines, and ecosystems, who also have agency
Linear Cause & Effect Thinking Environmental damage is the result of direct human action.	Distributed Causality Events emerge from complex material interactions, not just human intent.
Local & National Solutions Environmental issues are addressed at local, national, or regional levels.	Planetary-Scale Thinking Climate change, biodiversity loss, and pollution are global phenomena requiring interconnected approaches.
Examples of Scholars: René Descartes, Francis Bacon, John Locke, G.W.F. Hegel	Examples of Scholars: Donna Haraway, Bruno Latour, Jane Bennett, Timothy Morton, Dipesh Chakrabarty

3.2 Land stewardship in the Anthropocene

Environmental stewardship involves proactive efforts to protect and manage natural resources, including land and soil (Bennett *et al.*, 2018). Emerging perspectives, rooted in relational, new materialist, and post-humanist thought, critique traditional stewardship for isolating environmental, social, cultural, and technological factors, limiting its effectiveness (Twomey *et al.*, 2025). Scholars argue that addressing the complex challenges of the Anthropocene requires stewardship to evolve into a holistic, cooperative, and resilient practice, moving beyond conventional sustainable development (Chapin, Kofinas and Folke, 2009; Steffen *et al.*, 2011; Bennett *et al.*, 2018). The entangled ecologies of human and non-human systems require a radical rethinking of ethical responsibilities in environmental stewardship—one that embraces relational values (West *et al.*, 2018), redefines responsibility through post-humanist and situated ethics (Fuchsberger and Frauenberger, 2025), and expands notions of justice to include multispecies relations (Tschakert *et al.*, 2021).

3.2.1 More-than-human Stewardship

Val Plumwood (1993) critiqued the human/nature dualism in Western thought, arguing that ecological crises stem from the 'standpoint of mastery'—a view of nature as a resource to control and exploit—driving environmental degradation and social injustice, especially in the Anthropocene. Building on

Arne Naess' (1987) concept of the *ecological self*[7], Plumwood (2002) advocated for a reconceptualization of human identity that repositions humans as participants within ecological systems rather than as external rulers—emphasising a self that experiences the flourishing of others as integral to its own flourishing. This perspective challenges the modern notion of human exceptionalism and calls for an ethics grounded in interspecies mutuality. Haraway (2016, 2008, 2003) critiques human-centred stewardship for its top-down control and advocates instead for a multispecies ethics grounded in *sympoiesis*—collaborative *becoming-with* other species. They reject the Anthropocene's framing of humanity as a dominant force, and introduces the *Chthulucene*, a term that emphasises that survival depends on collaborative, situated, and relational practices, not human control or management. The concept of *response-ability* moves beyond anthropocentrism, by calling for an ethic of reciprocal engagement that acknowledges the entangled nature of the more-than-human world. Central to this shift is *making kin*—forging non-hierarchical relationships with animals, plants, and microbes to co-create futures rooted in mutual survival and flourishing (Haraway, 2016). Similarly, ANT proposes that outcomes arise not from individual intentions but from complex relationships. While traditional environmental stewardship assumes that humans are in charge and should protect or conserve nature, this perspective removes the traditional boundary between humans as managers and nature as a passive entity. ANT calls for negotiation with nature, as humans as just one actor among many. Stewardship thus becomes about cultivating better relationships with microbial communities, plant roots, and climate systems (Latour, 2005).

3.2.2 Planetary Stewardship

The notion of the Anthropocene forces humanity to recognise our role as planetary agents, stewarding hyperobjects and reshaping the planet, and exposes the gap between human actions and planetary consequences. Chakrabarty (2021) contends that climate change merges human and natural histories, requiring political and ethical responsibility beyond nation-states. Neither local initiatives nor fragmented global governance can adequately address superwicked planetary crises, necessitating new frameworks that transcend local and global scales toward a planetary approach to environmental stewardship — a need underscored by scholars such as Paul Crutzen (2002). Johan Rockström (2009) and Will Steffen (2011). Hence, Rockström *et al.* (2009) developed the concept of *planetary boundaries*, identifying nine critical Earth system processes that are crucial for maintaining a stable and habitable planet and whose disruption could lead to irreversible planetary tipping points, using the comparatively stable Holocene. These boundaries include climate change (e.g. GHG levels, global warming), biodiversity loss (e.g. species extinction rates), biogeochemical flows (e.g. N and P cycles), land system change (e.g. deforestation, land degradation), freshwater use (e.g. water consumption, hydrological cycles), novel entities (e.g. chemical pollution, plastics), ocean acidification (e.g. CO_2 absorption, marine life impacts), atmospheric aerosol loading (e.g. air pollution, cloud formation) and stratospheric ozone depletion (e.g. ozone hole, UV radiation). The planetary boundaries framework is an effort to provide a scientific foundation for guiding environmental stewardship by defining the ecological limits within which humanity can safely operate. According to Richardson et al. (2023), the first six planetary boundaries, including land system change, have been transgressed. This indicates that human land use has exceeded the safe operating space necessary for maintaining Earth's stability. This transgression

[7] a concept in environmental philosophy positing the self as inherently interconnected with the natural world, challenging anthropocentric notions of identity (Naess, 1987).

has worsened since the last planetary boundary assessment (Steffen *et al.*, 2015)signalling an increasing risk to the resilience of the Earth's soil system. The planetary boundary for land system change is measured using forest cover remaining as the key control variable. Forests play a crucial role in maintaining ecological balance, regulating the climate, and supporting biodiversity. To stay within safe limits, at least 85% of boreal forests, 50% of temperate forests, and 85% of tropical forests should remain intact. However, the current global forest cover has declined to approximately 60% of its original extent, pushing this boundary into the zone of increasing risk. This loss is primarily driven by large-scale deforestation, agricultural expansion, and urbanisation (Richardson *et al.*, 2023)

3.3 Reframing Security in the Anthropocene

Security studies began in the 1940s as an interdisciplinary approach that emerged after World War II, stressing the need to combine military, social, and natural sciences to address uncertainties about nuclear weapons. In the 1950s and 1960s, security studies had a "Golden Age" influenced by nuclear strategy and game theory, with deterrence theory significantly impacting political decisions. After the 1960s, security studies specialised, becoming part of international relations and losing its interdisciplinary nature. Between 1965 and 1980, security studies were declining, while peace research developed as a distinct area, emphasising a humanistic and social science-based perspective, unlike the predominant Cold War lens of traditional security studies, which prioritised military power and state-centric threats over broader human and societal concerns. However, in the 1980s and 1990s, new theories in security studies emerged (Wæver and Buzan, 2013). Rothschild (1995) notes that security studies expanded both horizontally and vertically in the 1990s. This includes a downward extension from securing nations to securing individuals and an upward extension from the nation to the international system and biosphere. And vertically, from a narrow focus on military security to include multiple factors that underlie human well-being. *Human security* (HS), defined by the United Nations Development Programme (UNDP) in its *1994 Human Development Report,* represents a paradigm shift from a state-centred notion of security to one that prioritises the rights of individuals to live a life free from want, free from fear and with dignity. The report formalised this perspective into seven dimensions: economic, food, health, environmental, personal, community, and political security (UNDP, 1994). *The 2022 UNDP Special Report on Human Security* redefines the concept of HS by incorporating the planetary dimension. In the era of the Anthropocene, the nature of security has fundamentally shifted. The UNDP highlights that human-driven environmental changes, such as climate change, pose serious fundamental threats to human well-being (UNDP, 2022). This reframing reflects a paradigm shift from a primarily individual-centric model of security to one that recognises the entangled ecologies between people and the planet. It situates HS within broader frameworks, acknowledging the nexus between degradation of natural systems and social instability, economic vulnerability, and political unrest, and violent conflicts (Barnett and Adger, 2007; Fagan, 2017; Trombetta, 2022; Nguyen *et al.*, 2023).

3.4 The Concept of Agroecology

AE is described as a trans-disciplinary approach to agriculture that integrates ecological principles into agriculture to promote sustainable food systems that work *with*, rather than *against*, natural processes. It encompasses science, practice, and social movements aimed at transforming food systems to be more sustainable and equitable (Gliessman, 1990, 1997). In alignment with the post-humanistic ideas, AE view farming as not just about producing food; it becomes an ethical, ecological, and regenerative act - one that respects the land as a partner rather than a mere resource. Adopting an AE approach to land stewardship, could mean moving from extraction to regeneration by adopting farming methods that restore rather than deplete. AE is a holistic approach that supports the sustainable development of food systems while strengthening the foundation of HS across multiple dimensions. AE exemplifies an approach to environmental stewardship that addresses pressing challenges of the Anthropocene (Altieri and Nicholls, 2020).

The term *agroecology* emerged in scientific literature in the early 20th century, with researchers lik B.M. Bensin, applying ecological principles to agricultural studies (Bensin, 1928, 1930, 1935). From the 1930s to 1960s, AE was primarily a scientific discipline focused on the ecological aspects of agriculture, including crop ecology and the interrelationships among plants, animals, soils, and climate. Thus, AE was the fundamental science of agriculture. In the 1950s and 1960s, AE concepts evolved, highlighting biodiversity's role in pest management and soil health. (Wezel and Soldat, 2009; Wezel *et al.*, 2009). Scholars such as W. Tischler (Tischler, 1953, 1959, 1961, 1965) studied AE with an approach that integrates ecology with agronomy, focusing on biological interactions at the field or agroecosystem level. The research during this era stayed mainly academic, with minimal practical use in agriculture (Wezel and Soldat, 2009; Wezel *et al.*, 2009). The environmental movements of the 1960s and 1970s, responding to the adverse effects of industrialised agriculture and the Green Revolution, significantly influenced AE by advancing practices such as polyculture, organic farming, and reduced tillage. In the late 20th century, AE expanded as a science alongside AE movements, while increasingly integrating ecology into agriculture and addressing broader environmental and social concerns (Wezel and Soldat, 2009; Wezel *et al.*, 2009). Since the early 1980s, AE has evolved into a distinct conceptual framework that uses holistic methods to examine agroecosystems and conserve natural resources while managing sustainable systems (Douglass, 1984; Altieri, M.A., 1989; Gliessman, 1990, 1997). Building on these frameworks, Conway (1987) identified four essential attributes of agroecosystems: productivity, stability, sustainability, and equity. In the 1990s, AE became a global movement, especially in Latin America, where smallholder farmers and social organisations adopted it for food sovereignty and rural empowerment. Movements like *La Vía Campesina* promoted AE to resist corporate control over food systems and advocate for farmer-led, environmentally sustainable agriculture. (Martínez-Torres and Rosset, 2010; Rosset and Martínez-Torres, 2013). By the turn of the millennium, AE referred to either a political/social movement, an agricultural practice, or a scientific discipline. AE as a social movement advocating for food sovereignty, environmental justice, social justice, and the rights of marginalised groups and small-scale farmers, challenging the industrial agriculture model (Wezel *et al.*, 2009). Examples include international movements such as *La Vía Campesina,* as well as regional and national initiatives such as the *Alliance for Food Sovereignty in Africa (AFSA),* a pan-African movement, and *Frie Bønder – Levende Land* in Denmark. AE as a practice encompasses methods such as crop rotation, intercropping, and integrated pest management, aiming to minimise reliance on external inputs and enhance biodiversity (e.g. agroforestry). The science of AE studies the interactions between people, agricultural production and the environment, focusing on sustainable practices that balance production with environmental protection and rural development (Wezel *et al.*, 2009). In recent years, the spatial scale of AE has also expanded from the farm to incorporate the agroecosystem and entire food systems[8], with the original definitions broadened to encompass "the ecology of food systems" (Francis *et al.*, 2003; Gliessman, 2014, 2020). AE is now studied and implemented at multiple scales: 1) The field/plot scale - examining plant-soil interactions, pest management, and biodiversity. 2) The farm/agroecosystem scale – designing sustainable farms that integrate diverse agricultural practices. 3) The food-system scale – addressing food sovereignty, fair trade, and consumer-producer relationships (Wezel *et al.*, 2009). Today, AE is recognized by international organizations, such as FAO, as a key strategy for achieving sustainable food systems (FAO, 2018; HLPE, 2019). Research continues to expand, focusing on topics such as climate resilience, AF, and food justice. Barrios et al. (2020) present *The 10 Elements of Agroecology* as a framework to facilitate the transition to sustainable agriculture. Developed by the FAO, it serves as a tool to help policymakers, practitioners, and stakeholders in designing and assessing AE transitions. The authors argue that agriculture must transform to address food security challenges, biodiversity loss, and climate change while enhancing resilience and sustainability. It outlines ten interdependent principles: 1) Diversity, 2) co-creation and sharing of knowledge, 3) synergies, 4) efficiency, 5) recycling, 6) resilience, 7) human and social values, 8) culture and food traditions, 9) responsible governance, and 10) circular and solidarity economy. Based on Barrios et al.'s. (2020) policy-oriented framework, Wezel et al. (2020), made a scientific synthesis of AE as a science, set of practices, and social movement, focusing on AE principles that drive transformation. The paper compares its 13 principles with the FAO's 10 elements of AE, highlighting their complementarity while emphasising soil and animal health and distinguishing biodiversity from economic diversification. Wezel et. al. (2020) 13 AE principles are:

1) Recycling: To prioritise the use of locally sourced renewable resources and close the nutrient and biomass cycles.
2) Input reduction: Minimising or eliminating reliance on external inputs and increasing self-sufficiency.
3) Soil health: To maintain and improve soil health and functionality to boost plant growth, with a focus on managing organic matter and enhancing biological activity in the soil.
4) Animal welfare: Ensuring the health and welfare of animals.
5) Biodiversity: To maintain the overall biodiversity of agroecosystems across time and space, at field, farm, and landscape levels, by preserving and increasing species diversity, functional diversity, and genetic resources
6) Synergy: Foster positive ecological interactions, synergies, and integration.
7) Economic diversification: Ensuring economic diversification by expanding on-farm income sources, ensuring small-scale farmers have greater financial independence, opportunities for value addition, and the ability to respond to consumer demand.
8) Co-creation of knowledge: Promoting the co-creation and sharing of knowledge, integrating local and scientific innovations, particularly through farmer-to-farmer exchanges.
9) Social values and diets: To build food systems rooted in social values and local diets that reflect the culture, identity, traditions, and commitment to social and gender equity of communities, while promoting healthy, diverse, seasonal, and culturally appropriate foods.

[8] A food system includes all actors and interconnected activities that contribute to the production, collection, processing, distribution, consumption, and disposal (through loss or waste) of food products derived from agriculture (including livestock), forestry, fisheries, and the food industry, along with the wider economic, social, and environmental contexts in which these processes occur (Von Braun *et al.*, 2023).

10) Fairness: To ensure fairness through supporting dignified and sustainable livelihoods for all actors in food systems, particularly small-scale food producers, based on fair trade, fair employment, and equitable treatment of intellectual property rights.
11) Connectivity: Fostering Connectivity through proximity and trust between producers and consumers through fair, short distribution networks and by reintegrating food systems into local economies.
12) Land and natural resource governance: Strengthening institutional frameworks that recognise and support family farmers, smallholders, and peasant food producers as responsible stewards of natural and genetic resources, to ensure sustainable land and natural resource governance.
13) Participation: To encourage social organisation and greater participation in decision-making by both food producers and consumers, supporting decentralised governance and local adaptive management of agricultural and food systems (Wezel *et al.*, 2020).

3.4.1 Transition Theory

Barrios et al. (2020) and Wezel et al. (2020) both emphasise the need for a transition toward sustainable food systems through AE, but they emphasise different approaches. Firstly, they are focusing on different levels and actors involved in the process. Unlike Barrios et al. (2020), who focuses on policy and governance as the main drivers, Wezel et al. (2020) highlight the role of farmers, social movements, and local knowledge as drivers of change, as they see co-creation of knowledge and participatory governance as essential for a successful AE transition. Barrios et al. (2020) offers a broad entry point for systemic transformation, focused on visual narratives, public procurement and governance reform, while Wezel et al. (2020) presents a step-by-step, bottom-up and practice-based AE transformation and references *The Five Levels of AE Transition (Gliessman's Model)* (Gliessman, 2014, 2016, 2020). In this model, AE offers a framework for transforming food systems—from improving resource efficiency to complete system redesign, encompassing all activities from production to disposal. It integrates science, practical methods, and social movements to promote ecological, economic, and social sustainability. This transformation demands participatory, transdisciplinary, and action-oriented research. Five key entry points have been identified to drive this change:

Level 1 – Increase Efficiency of Industrial Agriculture:
Reduce reliance on harmful inputs like synthetic fertilisers and pesticides by using precision agriculture to optimise input use. However, this approach maintains dependency on industrial systems.

Level 2 – Substitute Alternative Practices:
Replace synthetic inputs with organic or ecological methods (e.g., N-fixing crops, natural pest control). While more sustainable, the core agroecosystem remains largely unchanged.

Level 3 – Redesign Agroecosystems: Moves beyond substitution to structurally transform farming systems. This level aims at preventing problems rather than reacting to them, by focusing on diversity (e.g., crop rotation, intercropping, AF, integrating animals).

Level 4 – Strengthen Farmer-Consumer Relationships:
Promote local food systems and direct engagement through farmers' markets, community-supported agriculture (CSA), and cooperatives, while encouraging "food citizenship," where consumers actively support sustainable practices.

Level 5 – Transform the Global Food System:
Address systemic issues like climate change, food justice, and sustainability. This level calls for a fundamental shift in values, ethics, and policies to create an equitable, democratic, and sustainable global food system to sustain long-term change.

The initial three levels outline practical steps farmers can implement on their farms to transition from industrial or conventional agroecosystems. The remaining two levels extend beyond farming, addressing the broader food system and the societies in which they operate. Gliessman (2020) claim that AE is not just a technical approach but a systemic transformation requiring changes in culture, policies, and social structures. They call for a paradigm shift, rethinking human relationships with food, nature, and each other.

3.4.2 Lack of Transdisciplinarity and Knowledge Integration

AE is often described as a holistic transdisciplinary science because it aims to integrate different knowledge systems, ranging from biophysical sciences (ecology, agronomy, soil science) to social sciences (economy, sociology, anthropology) and even traditional and indigenous knowledge. However, the extent to which AE truly achieves these objectives is debated. While recognising the value of AE in promoting sustainable agriculture, some scholars argue it remains confined to traditional disciplinary silos (e.g. Dalgaard *et al.*, 2003; Dumont *et al.*, 2021; Einbinder *et al.*, 2022; Galt *et al.,* 2024; Méndez *et al.,* 2013). Méndez *et al.* (2013) critique AE for it's narrow natural science approaches and lack of transdisciplinary perspectives, arguing that AE must integrate social, cultural, and political dimensions to address food system challenges holistically. Agroecology has strong potential to transform food systems not just ecologically but also socially - yet its full transformative promise is limited by insufficient attention to human and social values such as social well-being, livelihoods, meaningful work, gender, and racial equity (Kerr *et al.*, 2022). Pinzón *et al.* (2023) and Galt *et al.* (2024) both examined AE's relationship with the social sciences and provided empirical evidence demonstrating that while engagement has increased, it remains inconsistent. Galt *et al.* (2024) find that the integration with social sciences has grown significantly, indicating a broader acceptance of interdisciplinary approaches. However, they critique that AE publications remain disproportionately focused on biophysical research and argue that AE's expansion is hindered by its uneven integration across disciplines. They argue that true large-scale implementation requires a transdisciplinary approach and suggest that AE's transdisciplinary potential is still underdeveloped, limiting the field's ability to address systemic agrifood challenges holistically. Dalgaard *et al.* (2003) contend that AE, though an emerging field, has yet to fully mature as a scientific discipline. They critically examine AE's position as a scientific discipline and discuss the challenges of integrating social, ecological, and political aspects within AE. They assess it against Mertonian norms of science (Merton, R. K., 1942) - communality[9], universalism[10], disinterestedness[11], and organised scepticism[12] - concluding that while AE meets many of these criteria, it diverges in key aspects. While they consider the integration of social and political dimensions valuable, their analysis raises concerns about the scientific rigour and methodological

[9] Common ownership of scientific knowledge to ensure open sharing.
[10] The evaluation of claims based on impersonal criteria rather than personal attributes.
[11] Pursuit of knowledge for its own sake rather than for personal gain.
[12] Rigorous, critical scrutiny of all ideas and findings before acceptance.

consistency in AE research, which could be interpreted as a caution against its potential drift toward advocacy rather than empirical science.

Another critique raised by Dalgaard *et al.* (2003) is the difficulty of scaling AE research findings from small-scale experimental settings to larger administrative and policy levels. Many AE studies are conducted at the field or farm level, making it challenging to extrapolate findings to regional, national, or global contexts. This challenge restricts the practical application of AE in broader agricultural policies and economic systems. The authors suggest an interdisciplinary framework to address the gap but emphasise that substantial methodological advances are still necessary for widespread adoption. Dumont *et al.* (2021) expand this discussion by pointing to the variability in implementation across different contexts. They note that AE is not a one-size-fits-all approach, and that adaptation to local governance structures and socioeconomic conditions is necessary for its successful expansion. Méndez *et al.* (2013) further highlight how AE's mainstreaming into policy spaces risks diluting its transformative potential. They warn that if AE is absorbed into dominant agricultural paradigms without maintaining its participatory and action-oriented roots, it may be co-opted without meaningful structural change. Dumont *et al*. (2021) take this critique further, arguing that theoretical principles of AE often struggle to translate into actionable practices due to a lack of interdisciplinary frameworks that bridge ecological, social, and economic dimensions. Dumont *et al.* (2021) propose the establishment of interdisciplinary methods and standardised assessment frameworks to improve the comparability of AE performance across different regions and contexts. A more systematic approach would enable policymakers and institutions to provide stronger institutional support for AE transitions. Méndez *et al.* (2013) caution against reductionist interpretations that isolate AE from farmer knowledge and participatory research. Einbinder *et al.* (2022) point out that the disconnect between local farming knowledge and AE interventions hinders effective scaling. They argue that for AE to be successfully adopted at a larger scale, it must move beyond isolated case studies and foster meaningful partnerships with local communities. They emphasise a different aspect of scientific maturity by criticising how AE initiatives often fail to fully integrate indigenous knowledge. This may lead to knowledge gaps between scientists and practitioners. They argue that many development programs, despite their sustainability rhetoric, continue to impose external methods that do not align with local ecological and cultural contexts, leading to high abandonment rates of introduced practices. These critiques echo broader theoretical debates about the nature of knowledge itself. Haraway's (1988) theory of *situated knowledge* challenges the notion of objective, universal science by asserting that all knowledge is partial, embodied, and context dependent. She critiques the "view from nowhere" - the claim that scientific knowledge can be detached from the social, cultural, and historical conditions in which it is produced. Instead, Haraway argues that all knowledge arises from a specific position or standpoint, shaped by the knower's material and social location. In the context of AE this framework highlights that farmers' localised, experiential knowledge, which emerge from direct, long-term interactions with soils and ecosystems, must be recognised as a vital epistemic resource, rather than treated as a secondary or anecdotal supplement to scientific knowledge.

3.4.3 Recognising Entangled Ecologies in Scientific Inquiry

What has been referred to as *entangled ecologies* denotes the complex, interdependent, and co-constitutive relationships between human and non-human systems that unfold across multiple spatial and temporal scales. They are socioecological configurations in which human and non-human actors, forces, and systems (e.g. biological, social, cultural, economic, technological, geological, political, etc.) interact in complex, recursive, and non-linear ways, such that boundaries between nature and society are blurred or dissolved (Latour, 2005; Haraway, 2016; Morton, 2016). Within the Anthropocene, entangled ecologies highlight how environmental degradation, climate change, and social vulnerability are not separate phenomena but part of a shared web of cause and effect (Waters *et al.*, 2016; Eswaran, Lal and Reich, 2019; IPCC, 2023), requiring integrated and transdisciplinary approaches to research, ethics, and stewardship (West *et al.*, 2018; Fuchsberger and Frauenberger, 2025). Addressing these intertwined challenges demands transdisciplinary approaches that transcend conventional disciplinary silos and integrate the natural and social sciences in environmental research (Lang *et al.*, 2012; IPBES, 2018) - AE bring a key example (Méndez, Bacon and Cohen, 2013; Dumont, Wartenberg and Baret, 2021; Kerr *et al.*, 2022). The Anthropocene amplifies systemic entanglements, reshaping not only the Earth's biophysical systems but also the epistemological and ontological frameworks through which we understand them (Gibson and Venkateswar, 2015; Jensen, 2020). Its superwicked problems defy clear definition and exceed the capacity of any single discipline (Rittel and Webber, 1973; Levin *et al.*, 2012), rendering conventional boundaries of knowledge increasingly inadequate, destabilising traditional scientific disciplines and demanding new, hybrid forms of inquiry (Inkpen and DesRoches, 2019; Keenan, 2020; Lawrence *et al.*, 2022). What emerges is a tightening web of relationships and dependencies, or what we might call an *Anthropocene force*, that draws scientific domains together (Fig. 1). This force exerts epistemological and ontological pressure(Gibson and Venkateswar, 2015; Jensen, 2020), driven by the sheer complexity of the problems they seek to address.

The epistemological pressure arises from the inadequacy of reductionist frameworks to fully comprehend Anthropocene-scale phenomena - i.e. challenges such as climate change (IPCC, 2023), mass extinction (Ceballos, Ehrlich and Dirzo, 2017), land degradation (Smiraglia *et al.*, 2016) and socio-environmental injustices (Flocks and Monaghan, 2003), transcend traditional knowledge boundaries - undermining detached and siloed methods of knowledge production (Mitchell, Lemon and Lambrechts, 2020; Soriano, 2022). Traditional science, privileging objectivity and linear causality, struggles to address systems characterised by non-linearity, feedback loops, and emergent properties (Gallopín *et al.*, 2001; Gunaratne, 2003). Consequently, scientific inquiry must evolve toward more integrative, participatory, and reflexive models, embracing epistemological pluralism by valuing empirical, Indigenous, local, and experiential knowledge systems (Whyte, 2013; Berkes, 2018). For instance, conventional soil science tends to study soil chemically or physically—measuring pH, nutrient cycles, erosion rates - treating soil as a passive resource (Wezel *et al.*, 2009). However, a growing body of research highlights that soil is an active, historical, and co-

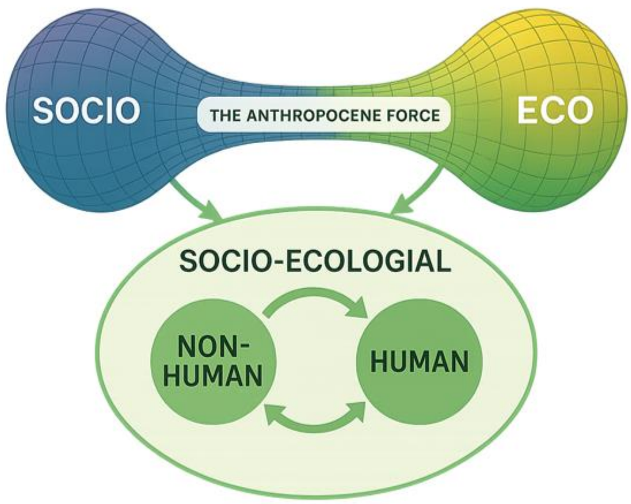

Figure 1.
The Anthropocene force enacts an ontological realignment of science, dissolving arbitrary disciplinary boundaries by exposing the entangled ecologies of the world. It prompts an epistemic convergence that brings together the social (political, cultural, social) and the ecological (physical, chemical, biological), redirecting scientific inquiry toward socioecology (*Ellesøe, 2025*).

constituted entity, intertwined with human cultures, agricultural practices, and governance systems (McNeill and Winiwarter, 2004; Hillel, 2009; Granjou and Salazar, 2019; Granjou and Meulemans, 2023). Studying soil adequately requires frameworks that integrate scientific methodologies with traditional ecological knowledge and lived experiences (Berkes, Colding and Folke, 2000; Gowing, Payton and Tenywa, 2004; Handayani and Prawito, 2010). Ontologically, the Anthropocene destabilises the nature/culture, human/non-human, subject/object binaries that have long structured Western scientific thought by revealing their arbitrariness (Latour, 1991; Descola and Sahlins, 2014).

Ontological pressure in the Anthropocene arises when those basic categories break down, requiring a conceptualisation of reality where entities are relational, entangled, and co-constituted (Kohn, 2015; Hamilton, 2016; Haraway, 2016; Morton, 2016). Soil, for instance, cannot be reduced to a passive "natural resource" but must be understood as a socio-material hybrid—emerging from biological, geological, and socio-political interactions over time (Blum, Warkentin and Frossard, 2006; Puig De La Bellacasa, 2019; Krzywoszynska and Marchesi, 2020). Together, epistemological and ontological pressures catalyse a reconfiguration of disciplinary boundaries, converging social and ecological domains into hybrid, transdisciplinary frameworks that recognise the entanglement of human and non-human systems. This convergence brings together the social sciences (political, cultural, social) and ecological sciences (physical, chemical, biological), redirecting inquiry toward *socioecology* (Folke *et al.*, 2002; Berkes, Colding and Folke, 2003), where nature and culture are no longer ontologically separate (Schoon and Van Der Leeuw, 2015; Jensen, 2020). In doing so, the Anthropocene redirects scientific inquiry toward acknowledging the socioecological co-constitution of planetary life (Lorimer, 2017; Reyers *et al.*, 2018).. Central to the socioecological thinking is the recognition that human actions are both shaped by and exert influence upon ecological processes, and the sustainability of both social and ecological domains depends on the feedback loops between them (Berkes, Colding and Folke, 2003). The resilience of a socioecological system depends not only on the ability of its ecological components to adapt but also on the capacity of human societies to adjust, manage change, and maintain functionality in the face of external pressures (Folke *et al.*, 2002)

3.4.4 Toward a Holistic and Transdisciplinary Agroecological Science

Transdisciplinary collaboration is essential for addressing the dynamic interactions between social and ecological processes in agroecosystems (Wezel *et al.*, 2020). A pressing question within AE discourse is how the movement can operationalise its transdisciplinary aspirations (See sec. 3.4.2). I argue that AE must move beyond nominal interdisciplinarity toward a genuinely holistic science, grounded in the recognition of socioecological entanglements and committed to methodological and epistemological plurality. Drawing inspiration from the HS framework (UNDP, 1994, 2022; Rothschild, 1995), I propose that AE sciences must simultaneously extend and maintain balance across three interconnected dimensions—horizontal, vertical, and scalar—to effectively recognise and engage with the entangled ecologies of the Anthropocene (Fig. 2).

Horizontally, AE must broaden its disciplinary scope by integrating the natural sciences (e.g., agronomy, soil science, ecology) with the social sciences (e.g., political ecology, cultural studies) and blending quantitative and qualitative methods (Méndez, Bacon and Cohen, 2013; Kerr *et al.*, 2022). Systems thinking, which embraces non-linearity, feedback loops, and emergent properties, is essential to understand AE systems as complex, interconnected systems (Vandermeer, 2020; Tittonell, 2023). A helpful metaphor is to imagine a complex, three-dimensional sculpture placed at the centre of a room. Each observer sees it from a different angle: one notices its curves, another its sharp edges, another its texture or shadow. None are wrong; each offers a valid yet partial truth. However, what they are observing are merely facets of a larger, interconnected whole. While each perspective is important, it is only through recognising that they are looking at the same figure that a fuller understanding can emerge. In much the same way, food systems are inherently multidimensional—ecological, social, cultural, economic, and spiritual—and these dimensions are deeply intertwined in ways no single disciplinary approach can fully capture (Méndez, Bacon and Cohen, 2013). Transdisciplinary research is essential for bridging these partial perspectives, bringing these diverse perspectives into dialogue and weaving them into a more holistic understanding of AE systems and their entangled ecologies.

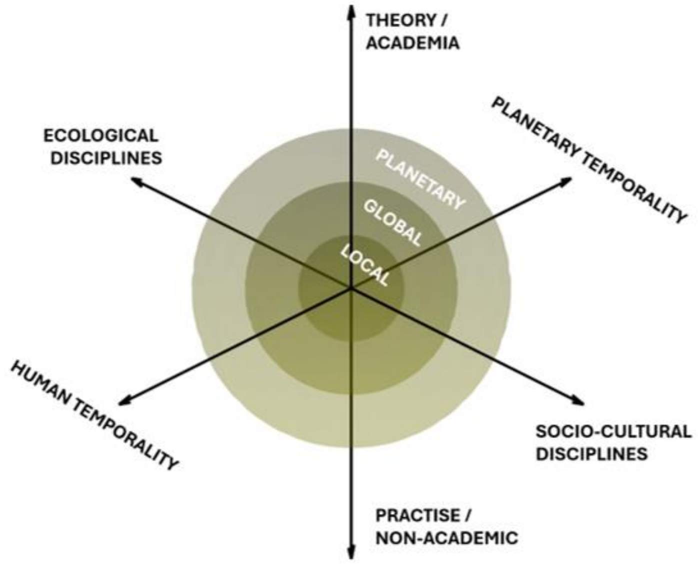

Figure 2
The Balance in agroecological research A Multidimensional Framework for Balance in Agroecological Research. The diagram illustrates the necessary balance in agroecological research across three intersecting dimensions: epistemological (from practice and non-academic knowledge to academic theory), disciplinary (spanning ecological to socio-cultural domains), and scalar-temporal (from local and human-temporal to planetary and long-term planetary-temporal perspectives). The concentric circles represent nested spatial scales—local, global, and planetary (Ellesøe, 2025).

Vertically, AE must broaden its epistemological base to incorporate not only Western scientific traditions but also Indigenous, local, and traditional knowledge systems (Berkes, Colding and Folke, 2000; Whyte, 2013; IPBES, 2018). Vertical expansion demands shifting the lenses through which we observe the sculpture. Some perspectives offer a surface-level view, while others, like an X-ray scanner, or thermal imaging, reveal hidden layers invisible to the naked eye, unveiling internal structures or exposing patterns otherwise concealed. Some lenses are familiar (e.g. conventional scientific methods), while others are lenses, we can only imagine, rooted in Indigenous cosmologies and long-standing experiential practices. While conventional scientific methods remain essential, integrating alternative knowledge systems may offer additional empirical insights that deepen our understanding, enriching AE science, and enabling it to capture dimensions often overlooked by the current paradigm. Further, this would be a means of truly valuing the principles of co-creation of knowledge, participation, social values, and food cultures (Wezel *et al.*, 2020), and that they are crucial for providing place-based adaptive strategies, particularly in contexts confronting the compounded effects of climate change and socio-economic marginalisation (Altieri and Nicholls, 2020; FAO, 2018).

In a third, AE should move from the local to the global, and to the planetary scale in its orientation in time and space. While rooted in local contexts, AE practices and research must also be situated within broader systems: global food systems and the planetary boundaries that define ecological sustainability. This scalar thinking is critical in the context of the Anthropocene, where local actions are intimately connected to global and planetary outcomes (Steffen *et al.*, 2011; Waters *et al.*, 2016; Chakrabarty, 2021). Scalar expansion is necessary for AE to move beyond local field- and farm-level studies to incorporate global and planetary perspectives (Dalgaard, Hutchings and Porter, 2003; Steffen *et al.*, 2011). While AE practices are grounded in local contexts, they are embedded within global food systems and must operate within the ecological limits defined by planetary boundaries (Rockström *et al.*, 2009; Richardson *et al.*, 2023). The Anthropocene necessitates that AE address both localized impacts—such as soil degradation and land-use change—and their cumulative contributions to global processes like carbon cycling and biodiversity loss, and vice versa (Lal, 2001; Eswaran, Lal and Reich, 2019). Moreover, scalar thinking must, account for the fact that local and planetary processes unfold across distinct temporalities, intertwining short-term human activities with the deep time of geological and Earth system transformations (Chakrabarty, 2021).

Together, these three dimensions reflect a commitment to epistemological plurality, socio-ecological justice, and long-term planetary stewardship—principles that resonate with post-humanist and Anthropocene discourses. ANT offers a powerful conceptual framework for advancing AE science by encouraging systems thinking and relational research practices. Methodologically, ANT invites researchers to "follow the actors" (Latour, 2005). For example, tracing how soil is co-produced through the interactions between microbial communities, farmers' traditional soil knowledge, vegetation, climate impacts, soil monitoring technologies, and agricultural extension work.

4. AGROFORESTRY – AN AGROECOLOGICAL APPROACH TO SOIL MANAGEMENT

Agroforestry (AF) is an AE land use system that integrates trees and shrubs with crops and/or livestock on the same land (Fahad *et al.*, 2022). AF is increasingly recognized as a viable climate adaptation strategy, particularly for enhancing soil health (Fahad *et al.*, 2022; IPCC, 2023), while also addressing other AE principles and HS issues.

4.1 Soil Organic Matter and Soil Structure

Soil structure refers to the arrangement of soil particles (sand, silt, and clay) into aggregates and the configuration of the pores between them. This structure is crucial for various soil functions, including water retention, nutrient cycling, root growth and soil erosion control (Fahad *et al.*, 2022; Yudina and Kuzyakov, 2023). AF systems (AFS) contributes to higher soil organic matter (SOM) levels because trees produce significant amounts of biomass, including leaf litter, fine root turnover, and decomposing branches, which enrich the SOC (Stefano and Jacobson, 2017; Dollinger and Jose, 2018). For instance, a meta-study by (Pan *et al.*, 2025) found that, on average, AFS have significantly 10.7% higher SOC compared to other land uses (i.e. cropland and forest). In a meta study conducted by (Muchane *et al.*, 2020) focused on humid and sub-humid tropics, the presence of trees in AF systems increased SOC levels by 21 %, compared to monocropping systems. SOM acts as a primary binding agent, facilitating the clustering and cohesion of mineral particles to form aggregates. This is supported by the presence of SOC in both particulate and dissolved forms, which significantly contributes to the formation of large, water-stable macroaggregates (Bucka *et al.*, 2019; Li *et al.*, 2023). Organic matter, particularly fresh inputs, contributes to macroaggregate formation, while microaggregates are often stabilized by intrinsic cementing through carbonates (Dalal and Bridge, 2020; Pihlap, Steffens and Kögel-Knabner, 2021). Tree roots also promote the formation of stable soil aggregates through the secretion of carbonaceous root exudates (Habib *et al.*, 1990; Baumert *et al.*, 2018). The root systems of trees and understory vegetation form a dense network that physically stabilises soil by holding particles together, enhancing cohesion, preventing landslides, and reducing susceptibility to wind and water erosion.

(Vannoppen *et al.*, 2017; Hairiah *et al.*, 2020). The extensive root networks of trees and understory vegetation create macropores in the soil, increasing porosity and reducing compaction (Udawatta *et al.*, 2006; Udawatta and Anderson, 2008). A higher SOM content lowers bulk density by increasing the proportion of lightweight organic materials in the soil matrix (Ruehlmann and Körschens, 2009). Hence, AF approach aligns with the AE principle on maintaining and improving soil health by preventing erosion, managing organic matter and promoting soil life for healthier plant growth (Principle 3, Wezel et al. 2020), by harnessing the beneficial synergies between trees and soil (P. 6).

4.2 Water management

Trees impact numerous soil hydrological processes, as enhanced soil structure and porosity allow for better water infiltration and retention. This maintains moisture during dry periods and prevents excess water in wet conditions (Fahad *et al.*, 2022; Rolo *et al.*, 2023), making AF regulate soil moisture fluctuations better than conventional crop management (Lin, 2007). AF systems stabilise microclimates by intercepting solar radiation and reducing temperature extremes, especially in shaded coffee plantations where maximum temperatures are lower than in unshaded areas. This effect mitigates fluctuations in soil and air temperatures, providing protection against extreme variations and reducing evaporation (Lin, 2010; De Carvalho *et al.*, 2021). AF effectiveness in regulating microclimates depends on canopy structure and tree density, with denser canopies enhancing thermal buffering and moisture retention (Martius *et al.*, 2004; Merle *et al.*, 2022). Some trees facilitate *hydraulic lift,* by redistributing water from deep soil layers to the upper layers, helping crops during dry periods and increasing resilience to droughts (Bayala and Prieto, 2019). This reflects the AE principle of input reduction, as AF minimises the need for irrigation by enhancing natural water retention in the soil (P.2).

4.3 Soil biota

AFS stabilises the microclimate, lowers soil temperatures, and maintains consistent moisture, benefiting soil microbial communities by increasing their diversity and abundance (Fahad *et al.*, 2022). Studies suggest that AF generally support more diverse soil biota (e.g., soil fauna and microorganisms) than monocultures, though not as much as natural forests (Marsden *et al.*, 2019; Visscher *et al.*, 2023). The structural and functional diversity introduced by trees creates habitat heterogeneity and enriches the soil with organic matter, supporting soil organisms (Nascimento *et al.*, 2024). The higher SOM in AF supports diverse invertebrate communities that enhance soil aeration through bioturbation[13]. Studies have shown AF with crops like coffee (*Coffea* spp.) and cacao (*Theobroma cacao*), promote soil macrofauna (such as earthworms, ants, and termites) which are vital for soil fertility and structure. Earthworms, especially, aid aggregation by producing mucilage and stable casts that bind soil particles (Moço *et al.*, 2010; Azembouh *et al.*, 2021; Nascimento *et al.*, 2024).

Trees play a crucial role in supporting mycorrhizal fungi[14], particularly arbuscular mycorrhizal fungi (AMF), which form symbiotic associations with tree roots (Shukla *et al.*, 2012; Dobo, Asefa and Asfaw, 2017). Tree roots release exudates that modulate the rhizosphere[15], enhancing

[13] The physical movement of soil by fauna or plant roots (Ruiz, Hallett and Or, 2023).
[14] Mycorrhiza is the mutualistic symbiotic association between soilborne fungi and the roots of vascular plants (Ainsworth and Bisby, 2001)
[15]the region of soil near plant roots where chemistry and microbiology are influenced by their growth, respiration, and nutrient exchange (Lynch, 1994).

symbiosis with AMF. These metabolites serve as signals and nutrients, promoting fungal growth by stimulating hyphal[16] branching and nuclear division in AMF (Monther and Kamaruzaman, 2012). AMF extend hyphae into the soil, forming networks that physically and chemically bind soil particles. AMF contribute organic compounds, especially Glomalin-Related Soil Protein, which binds and stabilises SOM and sediments in aggregates (Yang *et al.*, 2017; Zhang, Dong and Shangguan, 2022). They enhance the formation of macroaggregates and slow their disintegration, improving aggregate stability (McGowan *et al.*, 2019; Morris *et al.*, 2019). Both AMF hyphae density and soil aggregation increase near trees (Dierks *et al.*, 2021), and the presence of AMF is positively correlated with the abundance of water-stable macroaggregates (Zhang *et al.*, 2020).

AF improves soil physical properties compared to conventional agriculture by enhancing structure and microbial habitats (De Carvalho *et al.*, 2021; Oliveira *et al.*, 2024). AFS reduce compaction, increases porosity, and enhances water-holding capacity (Alegre and Cassel, 1996; Rivest *et al.*, 2013). In contrast, conventional tillage and the use of heavy machinery lead to compaction, which increases bulk density and decreases infiltration (Kozlowski, 1999; Shaheb, Venkatesh and Shearer, 2021) and harms root growth, soil fauna, and microbial activity (Whalley, Dumitru and Dexter, 1995). Conservation tillage, common in AF, supports higher microbial biomass, better aggregate stability, and improved soil biochemical properties (Overstreet *et al.*, 2004; Emmerling, 2007; Rivest *et al.*, 2013). Further, AMF abundance provides bioprotection against soil-borne pathogens by enhancing plant immune responses and interacting with other beneficial soil microorganisms, which reduces the reliance on synthetic pesticides (Jeffries *et al.*, 2002; Harrier and Watson, 2004; Dey and Ghosh, 2022).

This illustrates that principal soil health (P. 3) is supported by the principle of ensuring animal health through improvements in habitat quality (P. 4) and heterogeneity, thereby enhancing biodiversity (P. 5). This synergy yields positive ecological interactions among trees, roots, fungi, and soil organisms (P. 3). It not only improves soil structure but also reduces reliance on pesticides and labour inputs (P. 2).

4.4 Soil Nutrients

AFS improve nutrient cycling by incorporating tree litter and organic matter into the soil, which decomposes and releases nutrients back into the soil (Isaac and Borden, 2019). AF enhance nutrient acquisition through diverse root interactions and architecture. These complementary structures improve nutrient uptake from various soil depths and areas, minimising competition (Sanchez, Buresh and Leakey, 1997; Isaac and Borden, 2019). Deep-rooted trees access nutrients from lower soil layers unavailable to shallow-rooted crops. This "nutrient uplift" recycles nutrients like N, P, and essential micronutrients back to the topsoil via leaf litter decomposition and root exudates (Pankaj *et al.*, 2023). AMF form symbiotic relationships with most land plants, enhancing nutrient uptake, particularly P and N (George, Marschner and Jakobsen, 1995; Bücking and Kafle, 2015). AMF's extensive hyphal networks access soil micropores, effectively increasing the root surface area for nutrient absorption (Khade and Rodrigues, 2009).

[16] The fundamental filamentous structure that constitutes fungus (Weston and Whittaker, 2004)

Integrating leguminous trees enables diazotrophic bacteria (e.g., *Rhizobium* spp.) in root nodules to convert atmospheric N (N_2) into bioavailable ammonium (NH_4^+), significantly enhancing N sources for crops (Nygren *et al.*, 2012; Munroe and Isaac, 2014). Symbiotic root interactions with phosphate-solubilizing bacteria (PSB) and fungi (PSF), like AMF, enhance P solubilisation by releasing organic acids and phosphatases[17] that convert insoluble inorganic P into accessible forms for plants. In return, trees provide AMF with carbohydrates and lipids derived from photosynthesis (Ordoñez *et al.*, 2016; Jiang *et al.*, 2020). Hence, while trees do not supply P, they enhance its availability and uptake (Kuyah *et al.*, 2019), compared to conventional agricultural practices (Muchane *et al.*, 2020). The decomposition of tree litter and root biomass increases SOM, enhancing the chelation and bioavailability of essential micronutrients like zinc (Zn), iron (Fe), and manganese (Mn), vital for plant enzymatic and metabolic functions (Kaur, Singh and Dhaliwal, 2020).

Besides making nutrients more available, AF can improve nutrient retention and reduce nutrient losses through leaching (Tully, Lawrence and Scanlon, 2012), as tree rows act as a "safety net," reducing nitrate-leaching by up to 82% compared to monocultures(Schmidt *et al.*, 2020). Soil erosion is a major contributor to nutrient depletion, leading to significant losses of essential elements like N, P, and potassium (K) (Våje, Singh and Lal, 2005; Meena *et al.*, 2017; Bashagaluke *et al.*, 2018). Muchane *et al.* (2020) found that AFS can reduce soil erosion rates by 50% due to improved infiltration, decreased runoff, a higher proportion of soil macroaggregates, and enhanced structural stability of the soil. AF systems have been shown to significantly lower N-losses as gaseous nitric oxide (N_2O) emissions compared to conventional agricultural practices (Franzluebbers *et al.*, 2017; Gross *et al.*, 2022). However, AFS with leguminous trees can increase N_2O due to higher N input from N_2 fixation or fertilisers. Well-managed AFs (e.g., with controlled N input and moisture balance) may reduce N_2O, but some setups, particularly those with dense canopy and fertiliser, can increase it (Kim and Isaac, 2022; Berhanu *et al.*, 2023). AF can significantly affect carbon sequestration in both aboveground (tree biomass) and belowground biomass (roots, hyphae, SOM, SOC). This dual sequestration potential is higher than in monoculture systems, thus mitigating carbonic atmospheric GHG such as carbon dioxide (CO_2) and methane (CH_4) (Abbas *et al.*, 2017; Torres *et al.*, 2017). This illustrates how soil health (P. 3) is supported by microbes (P. 5, P. 6) through processes such as recycling (P. 1), nutrient uplift, litter decomposition, and the maintenance of closed nutrient loops. Together, these microbial activities naturally supply nutrients and prevent losses, thereby reducing the need for external inputs like fertilisers (P. 2).

4.5 Livelihood Resilience

AF offers a promising strategy for building livelihood resilience and enhancing agricultural sustainability in the face of climate change (Quandt, Neufeldt and McCabe, 2017, 2019; Quandt, Neufeldt and Gorman, 2023). Healthy soil is vital for small-scale farmers, supporting economic, food, and environmental security. Studies show that AF can improve all five livelihood capital assets - financial, human, social, physical, and natural - compared to conventional farming. Crop diversification is important in AF as it enhances soil fertility by improving the physical, biological, and chemical properties of the soil. Hence, the principle of diversification is key to AF's contribution to livelihood resilience (Quandt, Neufeldt and McCabe, 2019). AFS improve resilience to climate change (Brown *et al.*, 2018; Satish *et*

[17] enzymes that hydrolyse phosphate groups from their substrates

al., 2024), and enhance ecosystem services such as soil structure improvement, water retention, and biodiversity preservation, which support socio-economic development (Köthke, Ahimbisibwe and Lippe, 2022; Mukhlis, Rizaludin and Hidayah, 2022; Girma, 2024). AF can decrease soil erosion rates by 50% compared to crop monocultures (Muchane *et al.*, 2020). In montane ecosystems AF have been shown to effectively prevent landslides and reduce soil erosion, as AF enhances soil structure, improves water management and slope stability compared to conventional agriculture (Purwaningsih, Sartohadi and Setiawan, 2020; Visscher *et al.*, 2023; Sittadewi *et al.*, 2024), thus safeguarding both human settlements and agricultural land. Further, the overall global warming potential of AFS is generally lower than that of conventional agricultural systems. This is due to reduced emissions of CO_2 and N_2O and increased methane (CH_4) uptake in soils under tree cover (Baah-Acheamfour *et al.*, 2016).

Healthy soils are crucial for sustainable agriculture, as it support crop productivity(Mamatha *et al.*, 2024). Ensuring long-term soil health ensures that land remains productive for future generations, allowing small-scale farmers to sustain their businesses (M. Tahat *et al.*, 2020; Handayani and Hale, 2022). For cash crops like *Coffea* spp., soil health directly impacts yields and farmer incomes (Carr, 1993; Nzeyimana, Hartemink and de Graaff, 2013). Research consistently shows that adopters of AF technologies experience improved welfare compared to non-adopters. AE contributes to rural livelihoods by providing additional income sources from timber, fuelwood, and fodder (Kinyili, Ndunda and Kitur, 2020). Studies in Zambia, Indonesia, Rwanda, Nigeria, Ethiopia, and Kenya report higher household incomes and farm revenues for AF adopters (Kiyani *et al.*, 2017; Tafere and Nigussie, 2018; Chavula and Hassen, 2022; Wijayanto *et al.*, 2022; Oparinde, 2023; Reinhard Endeki, Shadrack Kinyua Inoti, and Stanley M. Makindi, 2023). AF can significantly enhance smallholder farmers' income by diversifying income sources and reducing reliance on single crops, thereby mitigating the risks associated with market price fluctuations and crop failure, while also providing seasonal and year-round resource flow. By incorporating various tree species—such as fruit trees, timber trees, or other crops—farmers can diversify their sources of income or use in the household to reduce expenses (Duffy *et al.*, 2021; Mukhlis, Rizaludin and Hidayah, 2022; Girma, 2024).

For smallholder farmers, who often rely on subsistence farming, crop diversification is not only a critical strategy for enhancing economic security, but also a fundamental component for food security. By boosting agricultural productivity and offering a wider range of food sources, AF strengthens food security. It promotes greater dietary diversity and creates opportunities for off-farm employment, improving overall access to food (Duffy *et al.*, 2021; Gonçalves, Schlindwein and Martinelli, 2021). AF can strengthen the availability of food by increasing the production of diverse food products (fruits, nuts, vegetables, fodder), but also access to food by increasing income, enhancing purchasing power, and thus reducing household expenditure on food through self-sufficiency. AF also contributes to nutritional security, in terms of nutritional diversity and improved diet quality, and increased utilisation and by influencing the availability of cooked food, through the provision of wood-based fuel. AF can enhance food stability as it gives a steadier supply across seasons and greater resilience to climate-related food system shocks (Duffy *et al.*, 2021; Jemal, Callo-Concha and Van Noordwijk, 2021)

AF can also provide significant cultural benefits, contributing to broader socio-economic advantages. By integrating traditional practices with modern agricultural techniques, AF enhances community resilience and helps preserve cultural heritage. AFS often incorporate indigenous farming methods, maintaining ancestral traditions while promoting food security and income generation. Beyond their practical benefits, these practices also deepen spiritual connections and foster stronger relationships with nature (Gonçalves, Schlindwein and Martinelli, 2021). AF can stimulate cultural activities by promoting community engagement and cooperation in managing shared resources. It can also stimulate cultural activities and strengthen community ties, reinforcing a sense of identity and belonging that is essential for social cohesion in rural areas. (Gonçalves, Schlindwein and Martinelli, 2021; Mukhlis, Rizaludin and Hidayah, 2022). Further, AF can promote gender equality by involving women in management practices, which supports family food consumption and income generation. (Kiptot and Franzel, 2012; Gonçalves, Schlindwein and Martinelli, 2021). By diversifying farm activities, AF supports sustainable livelihoods, helping communities withstand environmental and economic shocks, but this diversification is culturally significant as it aligns with traditional practices of resource management and community resilience (Kuyah *et al.*, 2019).

5. THE PRODUCT

The product in this thesis is an article manuscript for the journal Ecology and Society. This exemplifies a scientific product that integrates knowledge and methods from both social and natural sciences. In this article, I bridge the gap between social-cultural and biophysical aspects of the socioecological AE system of Mount Elgon, in correspondence with the argument presented in this thesis report (See sec. 3.4.3-4).

5.1 Fieldwork with the AfPEC Project

The fieldwork for my manuscript was conducted as part of my internship with *Agroforestry for People, Environment, and Climate* (AfPEC)[18], a project operating in Mount Elgon in Uganda. The AfPEC project aims to document the effects of AF on ecosystem services and livelihoods, to address global challenges like climate change and biodiversity loss, while supporting local communities. It focuses on enhancing coffee AF practices with local farmers in the Mount Elgon region, involving three universities and three NGOs to combine research with practical applications. I chose to affiliate with AfPEC due to its strong connections with local communities and its objectives, which closely align Wezel et al.'s (2020) principles of AE, and with my research focus. Additionally, this affiliation resonated with my ethical considerations, as AfPEC actively collaborates with local partners and ensures its work is grounded in community needs. This project's relevance to my thesis lies in its transdisciplinary approach, integrating social and natural sciences. Its dual emphasis on research and development provides an ideal environment, as the AfPEC exemplifies how AE studies can address Anthropocene challenges, aligning with my thesis's focus on interdisciplinary collaboration.

5.2 Methodological Background Considerations

5.2.1 Grounded Theory

Grounded Theory (GT) is a qualitative research methodology widely used in social sciences to explore complex phenomena without relying on pre-existing theories. GT is inductive, generating theories from systematically collected data, like interviews and observations, rather than testing hypotheses.

[18] https://afpec.info/

The process follows an iterative cycle, where initial data analysis informs subsequent data collection, refining concepts and categories over time. Data collection is guided by emerging insights, keeping the theory rooted in real-world experiences (Tarozzi, 2020; Mohajan and Mohajan, 2022). GT thus facilitate an exploration of localised, situated knowledges (Haraway, 1988). This approach, therefore, foregrounds the agency of local actors in co-creating agroecological science.

One example of how I applied the GT methodology was by using the HS framework to guide my initial engagement with the communities during fieldwork. Before my immersive fieldwork, I attended community meetings and engaged in informal conversations with local youth members. My initial approach was broad: using the HS framework to explore and map the various challenges they faced in relation to agriculture. These discussions offered insights into the community's perceptions of insecurity within the framework and helped me identify recurring themes. Through conversations and observations of landscapes and local practices, I explored dimensions of security, allowing both human and non-human actants to express concerns in their own terms or emerge within the local context. One issue that consistently emerged in every conversation and was very visible in the landscape was soil degradation, particularly soil erosion and landslides (See picture 1a+b). This concern was not only prevalent but also deeply interconnected with multiple dimensions of HS, affecting livelihoods, food security, environmental sustainability, and overall community resilience. Given its significance and its complex socioecological entanglements, I decided to centre my research on soil-related challenges. With this refined focus, I conducted my immersive field work. In GT terms, soil-youth relations became my core category around which other sub-categories (e.g., tree-planting, barriers, motivations, environmental change, etc.) were organised. As my research progressed, I adopted an iterative

a)

b)

Picture 1:
a) A small-scale landslide struck a house directly, with displaced soil causing significant damage to the structure. A family of eight was still living in the house**. b)** A wider landscape view of a typical hillside in Mount Elgon, characterised by a mix of eucalyptus trees, coffee and multiple soil scars on the hillside, characteristic of previous landslides and severe erosion. The scattered vegetation and bare patches on the slope suggest areas of recent or recurring soil movement (*Ellesøe. 2024)*

approach, continuously refining my focus based on landscape/ecological observations and the concerns expressed by youth in interviews and daily interactions.

5.2.2 Integrating ANT thinking in Mixed-Methods Ethnopedology

Ethnopedology is an interdisciplinary field that draws on both the natural and social sciences to study rural populations' knowledge systems of soil and land, as well as how local communities perceive and manage land resources (Barrera-Bassols and Zinck, 2003). In the face of the Anthropocene, I find the ANT increasingly relevant to address the limitations of traditional soil science's narrow natural science focus and for understanding AE systems as socioecological systems. Thus, in this study, I employed an integrated mixed methods ethnopedological approach, drawing on ANT to better capture the entanglement between distributed networks of agency among human and non-human actors co-producing soil realities in Mount Elgon. In my analysis, I "followed" three key actors that play a crucial role in the local security context - namely, soil, young farmers and trees (fig. 2):

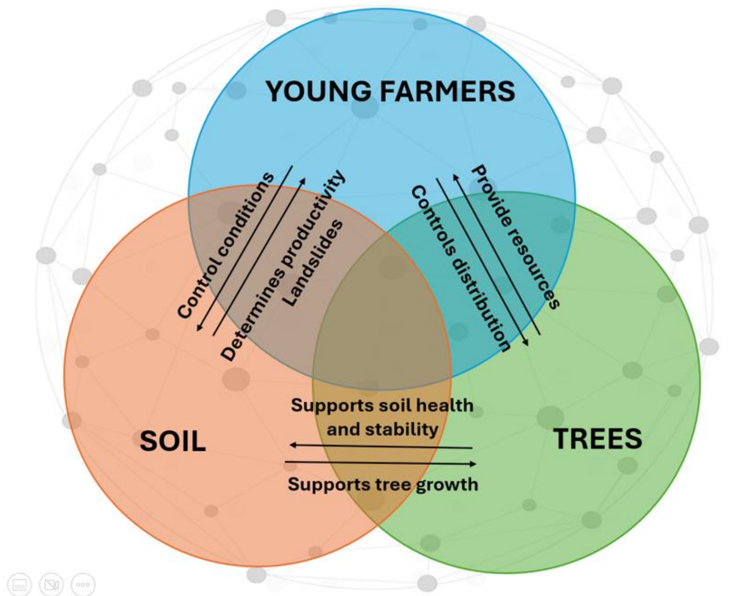

Figure 2: Actor-map illustrating the key stakeholders examined in the product article and summarising the network of relations through which they interact.

1) Soil forms the foundation of agricultural systems, as it underpins plant productivity by supplying nutrients, retaining moisture, and providing structural support. However, mountainous terrain and erosion-prone soils heighten vulnerability to degradation. Soil erosion in Mount Elgon poses a significant security risk and is driven by steep terrain, intense rainfall, and human activities (Bagoora, 1988; Jiang, Bamutaze and Pilesjö, 2014), including population pressure, deforestation, and poor farming practices (Buyinza and Mugagga, 2010). Models estimate significant soil loss, with 63% of the catchment exceeding 10 t ha-1 yr-1. Without proper management, this soil instability can lead to humanitarian and environmental crises (Bamutaze *et al.*, 2021). Trees enhance soil stability through the addition of organic matter, stabilisation of soil structure, and improvement of microbial activity (See sec. 4), while the fertility and physical integrity of the soil largely determine the productive capacity of trees and crops. Therefore, soil operates both as a determinant of productivity and as a producer and recipient of ecological services. However, soil conditions directly influence the decisions made by young farmers.

2) Youth under the age of 30 comprise over 70% of Uganda's population (UBOS, 2024), and the majority dependent on agriculture for their livelihoods, young people are particularly vulnerable to land degradation and climate-related risks (IPCC, 2023). As emerging stewards of the land, their role is crucial in shaping local landscapes through their agricultural decisions. They directly influence the soil conditions through their choices and interventions, such as applying inputs, implementing conservation practices, or tree planting. They act as managers and facilitators within the agricultural system,

mediating the interactions between non-human actors such as soil and vegetation. Thus, they are gatekeepers for AE transitions, with their capacity to make environmentally sound decisions directly influencing the system's overall resilience and impacting other human and non-human actors.

3) Trees function as stabilisers and ecological enhancers that provide ecosystem services, such as carbon sequestration and erosion control, to both human and non-human actors (See sec. 4). Young farmers largely control the distribution and management of trees, as deforestation is driven by human activities such as agricultural expansion, logging, and charcoal production. They depend on soil health for support and nutrient uptake, while simultaneously contributing to soil enrichment and long-term fertility. Trees shape soil quality and impact young farmers' livelihoods through access to tree products.

Several key findings would have been missed in a narrow natural science non-participatory study, including the social barriers young farmers face in adopting agroforestry, their short-term economic priorities, culturally grounded species preferences, and the importance of peer learning and local perceptions in shaping soil management - insights that only emerged through participatory engagement. Further, the integrative methodology challenged the traditional separation between social and ecological systems, prompting me to critically reassess internalised assumptions, particularly the human–nature binary and the view of agriculture as an exclusively human-driven enterprise. It enabled this integration by considering both the farmer's experience of soil and the soil's agency on its own terms - first seeing the soil through the farmer's eyes (perceptions), then interpreting the condition of the soil (water stable aggregate metrics), ultimately merging both viewpoints into a unified analysis. Examples of relations that would not have been found without using both social and natural science methods include: 1) The study found that perceived erosion risk (reported by farmers) was not significantly correlated with measured Wet Stable Aggregate metrics (WSA), a scientific indicator of soil structure, though it did correlate with observed erosion signs. Without integrating soil science measurements and farmers' perceptions, this disjuncture would not have been evident. It highlights how farmers' risk assessments are based more on visible surface cues than subsurface soil structure. 2) Using soil sample analysis, the study found that Cordia spp. Density was positively correlated with WSA metrics, while Ficus spp. showed negative correlations. Simultaneously, interviews showed farmers subjectively favouring *Cordia* spp. and disfavouring *Eucalyptus* spp. for their soil-enhancing properties. The study could only confirm or nuance farmers' experiential knowledge with empirical soil health data by combining the biological soil testing and farmers' species preferences. 3) Quantitative analysis showed a negative correlation between above-ground tree biomass and perceived erosion, while farmers often mentioned that more tree cover prevents soil erosion. The use of AGB measurements and farmers' perceptions together provided a feedback loop linking actual biophysical conditions with local knowledge, validating or nuancing the farmers' environmental intuition. Hence, this integrated approach revealed the co-constitutive relationship between soil, trees and farmer, forming dynamic, nonverbal and non-linear feedback loops.

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