THE ADOPTION AND IMPACTS OF NATURE-BASED SOLUTIONS ON SMALLHOLDER FARMS IN SEMI-ARID KENYA

By

Andrew Christopher Janzen Enns

A Thesis submitted to the Faculty of Graduate and Postdoctoral Studies of

The University of Manitoba

in partial fulfilment of the degree of

MASTER OF SCIENCE

Department of Plant Science

University of Manitoba

Winnipeg, Manitoba,

Canada

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ABSTRACT

Enns, Andrew C. J., M.Sc., The University of Manitoba. 2026. The Adoption and Impacts of Nature-Based Solutions on Smallholder Farms in Semi-Arid Kenya. Major supervisor: Dr. Martin H. Entz.

Solutions are needed to confront the combined challenges of climate change, landscape degradation, biodiversity loss, food insecurity, and poverty that Kenyan small holder farmers face. Nature-based solutions (NbS) are a proposed means of addressing these problems. Two NbS are highlighted in this thesis: farmer managed natural regeneration (FMNR) and conservation agriculture (CA). There are two objectives of this thesis. First, evaluate what influences farmer willingness to adopt these practices, thereby identifying what practices inhibit and facilitate adoption. The study uses logistic regression and a survey of 1,529 Kenyan farmers in Kitui and Makueni County, Kenya. A Lack of information and training was the primary factor limiting adoption of the NbS. Disasters such as floods, droughts, and biotic stresses (i.e. pests and diseases) increased adoption of NbS in many instances. To a lessor extent, higher incomes and food security also promoted adoption of these practices. These results enable policymakers, non-governmental organizations, and research staff to provide better support for East African small-holder famers and enable them to increase their resilience to the challenges they face.

Second, a field study assessed how FMNR is affecting agroecosystems by measuring its impacts on soil health, insect biodiversity, ground cover, and herbaceous biomass production compared to a business-as-usual (BAU) treatment. After only two growing seasons the impacts of FMNR were tangible and identifiable by the farmers. Soil health as measured by soil respiration increased as did farmer led measures of soil health. Insect diversity, as assessed by Hill numbers was greater in the FMNR plots compared to the BAU when considering insects captured in pitfall traps. Biomass and ground cover were also significantly higher in the FMNR plots compared to the BAU plots. Together these results highlight the ability of FMNR to offer significant farmer-observable impacts on the local environment over short time spans. These impacts contribute to addressing declining soil health, biodiversity and restoring overall

landscape productivity. Taken together, the two studies in this thesis help support increased adoption of FMNR and identify the subsequent benefits of adoption on agroecosystems.

ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Dr. Martin Entz, for the support and guidance you provided me, which helped me navigate working on a project set in an unfamiliar environment and all the complications that come along with that. I also want to thank my advisory committee members, Dr. Iain Davidson-Hunt, Dr. Jason Gibbs, and Dr. Inoka Amarakoon, for your support and valuable feedback.

A special thanks to all the Canadian Foodgrains Bank staff and partners, especially the entire Kenya team. This project would not have been possible without their collective efforts. In particular, thank you to Joyce Mbingo for your role in helping coordinate visits, taking the time to travel to field sites with me, following up with local partners to ensure work was being done, answering my questions, and the countless other ways you helped me complete this project; John Mbae for your assistance in the field; and Florence Nduku for your manuscript feedback and support during field visits.

The ADRA Kenya staff were another vital partner in helping me complete this project, and I am grateful for their support. Thank you especially to Nathanael Kitheka for your crucial role in data collection. Similarly, I would like to thank Naomi Kinya and Southeastern Kenya University for their support in analyzing and processing samples. Thank you to the farmers who volunteered to participate in the project. Again, this work would not have been possible without their participation and support.

Thank you also to fellow lab member Sasha Loewen for your mentorship, guidance, and help throughout all parts of my project, as well as Michelle Carkner for your advice and support.

The Canadian Foodgrains Bank and the Jarislowsky Foundation provided financial support for this project. I would also like to thank the Samit and Reshma Sharma Foundation for providing additional funding for my research through their scholarship.

Finally, thank you to my parents for their unending encouragement and support. And to Soffia, thank you for helping me navigate the highs and lows of a graduate degree and for always being there for me.

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FORWARD

This thesis is written in the format of Agroecology and Sustainable Food Systems and follows the guidelines of the Faculty of Graduate and Postdoctoral Studies, University of Manitoba and the supplementary guidelines of the Department of Plant Science, University of Manitoba. This thesis is structured in manuscript style, it consists of preliminaries, introduction, four chapters and appendices. Chapter 1 consists of a literature review, while chapters 2 and 3 are research chapters. Finally, chapter 4 is a general discussion. Chapter 2 was submitted to International Journal of Agricultural Sustainability on August 11, 2026, and is under review with the journal administrator.

INTRODUCTION

Anthropogenic climate change is rapidly altering the environments upon which small holder farmers rely (Nyandiko et al. 2015; IPCC 2023b). Warmer climates lead to exacerbated moisture deficits, while higher temperatures create heat stress and lower the photosynthetic efficiency of plants (Adhikari et al. 2015). Furthermore, rainfall patterns are predicted to become more erratic and intense, with arid and semi-arid regions projected to become more drought-prone throughout the coming decades (Haile et al. 2020). Drought affected areas in East Africa are projected to increase between 16% and 54% by the end of the century depending on future greenhouse gas emissions scenarios (Haile et al. 2020). Projected impacts of climate change on crop yields are extremely variable. In rare cases, such as in highland areas of Kenya, maize yield may increase due to historically lower temperatures, but the expected yield changes are broadly negative (Adhikari et al. 2015). In a survey of farmers from Kitui County, 96% of respondents reported noticing changes in temperature and 89% reported changes in rainfall. Ninety-seven percent of participants rated these changes as having negative impacts on production (Khisa 2018 July).

At a time when climatic stress is increasing, the resiliency of landscapes and agroecosystems has declined. Many landscapes are highly eroded (Lohbeck et al. 2018) and droughts can increase susceptibility to future erosion by reducing ground cover (Blake et al. 2018). as demand for land has intensified, Reductions in fallow periods, have removed opportunities for land to naturally regenerate, accelerating degradation (Rasmussen et al. 2018; Kuyah et al. 2023). Human land use, especially through deforestation and conversion of land for agricultural use, has resulted in large reduction in abundance and biodiversity of many organisms (Newbold et al. 2015; Balima et al. 2020; IPCC 2023b). These changes have degraded the adaptive capacities of unmanaged ecosystems as well as agroecosystems (Oliver et al. 2015).

Low food security and poverty have further limited the adaptive capacity of many farmers in Kenya/East Africa (Walpole et al. 2013). While less severe than in the past, extreme poverty remains high in Eastern and Southern Africa especially in rural areas (World Bank 2024). In 2024, 43.2% of people

lived below the $2.15 a day poverty line (World Bank 2024). Poverty can lower risk tolerances and willingness to try new, potentially beneficial practices that could help lift households out of poverty (Jumare et al. 2018). Globally, 500 million smallholder farmers produce more than 80% of the food consumed in developing countries (Walpole et al. 2013) and therefore are the essential stakeholder in addressing these problems.

Smallholder farming systems in sub-Saharan Africa are extremely diverse (Tittonell et al., 2010). They differ in key areas, including resource endowment (knowledge, land, labour, and capital), demographic and environmental context. Smallholder farmers produce the majority of food in sub-Saharan Africa (Giller et al. 2021a) and agriculture provides employment for roughly half of the region's population (World Bank 2025).

Not all agricultural development approaches are guaranteed to meet this multi-dimensional problem. As reviewed by Rasmussen et al. (2018), intensification often generates trade-offs between human benefits and environmental sustainability. In some cases, these trade-offs can result in "lose-lose" outcomes, whereby environmental degradation reduces future agricultural productivity. Nature-based solutions (NbS) have been proposed to address the interconnected challenges facing smallholder farmers (Key et al. 2021). While NbS have multiple definitions (European Commission 2015; Cohen-Shacham et al. 2016) the International Union for Conservation of Nature (IUCN) describes NbS as, "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016). NbS can be applied to many contexts beyond agriculture (Nyika and Dinka 2022). In contrast to many conventional forms of agricultural intensification, NbS and agroecological approaches, have been observed to simultaneously offer climate change mitigation and climate change adaptation while supporting ecosystem health and providing societal benefits (Bezner Kerr et al. 2021; Key et al. 2021).

Given the multifaceted challenges facing Kenyan farmers, a comprehensive understanding of how NbS can benefit farmers and their surrounding environment is needed. Furthermore, there is a need to assess when and why farmers are adopting these practices. Therefore, this master's thesis focuses on two NbS: Farmer managed natural regeneration (FMNR) and conservation agriculture (CA). Both are being promoted as part of the Canadian Foodgrains Bank's Nature+ program in Kenya. There are two objectives of this thesis. First, to understand what influences a farmer's decision to adopt CA or FMNR, as well as a closely associated practice known as enrichment planting. Second, this thesis aims to assess the impacts of FMNR on soil health, insect diversity, ground cover, and herbaceous biomass. Together these metrics help create a cohesive understanding of the non-human impacts of FMNR. It is hypothesized that FMNR will positively impact the local environment and resilience of landscapes observed through improved soil health, insect biodiversity, increased ground cover and increased biomass stockpiling.

CHAPTER 1. LITERATURE REVIEW

The objectives of this literature review are as follows: 1. Introduce the historical context and how biodiversity and soil health interplay within the context of East Africa; 2. Provide a detailed overview of farmer managed natural regeneration and conservation agriculture; 3. Review how these two practices have the potential to impact soil health and biodiversity as well as general benefits of these practices; 4. Review how the adoption of these two practices are influenced by various socioeconomic factors.

1.1 Historical Context

Agriculture in Kenya has gone through several paradigms. Prior to colonization, farmers in the region had developed localized agricultural practices which fit the environmental context and unique needs of farmers (McCann 1991). During the colonial period, which ended in 1963, agricultural policy was directed by the colonial government. This top-down approach failed to consider the cultural and practical needs of farmers, and it was assumed that innovations should be applicable to all farmers (Mukembo and Edwards 2016 Dec 1). In the latter half of the 20th century the green revolution became a dominant force in development policy (Dawson et al. 2016).

Despite its success elsewhere in the world, the green revolution has failed to meet its promised claims in most regions of Africa. Programs such as the Alliance for a Green Revolution in Africa (AGRA) have attempted to modernize African agriculture. According to critics, this program, which has relied heavily on input subsidies, has failed to meet its original goals (Wise 2020). Furthermore, Wise (2020) argues that AGRA has offered limited evidence of tangible impacts despite the roughly $1 billion in funding. Some African farmers have been able to adhere to these modernization policies, but these successes have been concentrated amongst wealthy farmers resulting in exacerbated wealth inequality (Dawson et al. 2016). In some cases, poor farmers have been adversely impacted by these green revolution practices. For example, the imposed technologies can result in a loss of local knowledge, trade, and can hinder land tenure (Dawson et al. 2016). Additionally, green revolution models often fail to replace the benefits and services that trees and natural ecosystems provide (Kibru et al. 2021). Top-down

tree planting projects, often funded by similar institutions pushing green revolutions approaches, also have been criticized for ignoring the needs of local communities and cultural realities (Zhu et al. 2025). These green revolution projects draw uncomfortable similarities to the top down one-size-fits-all approaches used by past colonial governments.

In contrast to green revolution methods, more participatory farmer-focused approaches have become popular (Mukembo and Edwards 2016 Dec 1; Bezner Kerr et al. 2021; Entz et al. 2022). This approach acknowledges the diversity of farmer needs and actively engages farmers in knowledge generation. NbS complements participatory approaches as it aims to be site-specific, culturally appropriate, and draw on traditional knowledge (Cohen-Shacham et al. 2016).

1.2 The Modern-day Kenyan Agricultural Context

Kenya contains a diverse spectrum of agriculture: nomadic or semi nomadic pastoralist communities, tea plantations, large flower farms, mechanized grain farms, and smallholder farmers. In semi-arid regions, which includes Kitui and Makueni Counties, landscapes may include a mix of rangeland, woodlots, and row crops. Smallholders dominate in these regions and are characterized by low levels of mechanization. Work is either performed by hand tools or by animal traction. Tractor use remains limited but is increasing. Similarly, the use of external inputs such as fertilizers and pesticides remains low and is highly variable. Common crops in Kitui include: maize (*Zea mays*), sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*), green grams (*Vigna radiata*), cowpeas (*Vigna unguiculata*), and pigeon peas (*Cajanus cajan*) (County Government of Kitui 2018).

On subsistence farms, much of what the farmer grows is consumed by the household. This has implications for what crops can be promoted. For example, a legume that tolerates drought may grow well in these regions but if it is not traditionally consumed by farmers, uptake may be very limited. Providing market access to allow farmers to grow and sell various crops in exchange for cash can provide an opportunity to reduce poverty and create interest in new crop types (Giller et al., 2021).

Yields in Kitui county are low and highly variable. Maize yields average 1370 kg ha^{-1} (SD = 1072 kg ha^{-1}). Average maize yields in Makueni are 1270 kg ha^{-1} (SD = 660 kg ha^{-1}) and don't show evidence of sustained yield increases (Nyandiko et al. 2015). Rainfall in the region follows a bimodal distribution with two growing seasons occurring per year (Figure 1-1). These two seasons are termed the short rains and the long rains.

Table 1. Overview of the annual growing seasons and key activities in Kitui County, Kenya.

Date	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Season	Short rains			Dry season		Long rains				Dry season		
Activity	Short season crops planted			Harvest		Planting maize				Harvest maize		

1.3 Biodiversity in the East African Agricultural Context

Globally, insect biodiversity has decreased by 45% (Wagner 2020). Land use changes are major drivers of this trend (Wagner 2020). The abundance and diversity of insects, especially pollinators, are critical for African agroecosystems (Teklewold et al. 2021; Mulungu et al. 2023). Consequently, biodiversity assessments are crucial for monitoring ecosystem health. Insects are particularly important taxonomic group for biodiversity monitoring, and their diversity can serve as a good indicator of broader biodiversity (Landmann et al. 2023).

While evidence points to sharp insect biodiversity losses worldwide, few studies have been conducted in African agroecosystems, and tropical landscapes in general are underrepresented in the literature (Wagner 2020). Therefore, there is a great need for additional research in tropical areas such as Africa. Furthermore, tropical areas consistently support larger amounts of biodiversity (Hillebrand and Thomas 2004), and this biodiversity is vulnerable to the impacts of climate change (IPCC 2023b).

Despite the importance of biodiversity, smallholder farmers may have limited knowledge of how beneficial insects interact with their cropping systems. For example, surveys on smallholder farmers in Tanzania (Elisante et al. 2019) reported that only 52% of farmers understood the role of honeybees as pollinators of crops, this increased to 80% when considering wild bees. Furthermore, most farmers did

not understand the benefits of field margins for potential insect habitat. This lack of understanding came up in personal communications with farmers, who questioned why a goal was to increase insect abundance while they were used to trying to kill insects. Ensuring farmers understand the benefit of insect diversity and abundance will be critical if they are to be a part of the solution to limiting further biodiversity loss.

Increasing insect biodiversity and abundance can improve food security for smallholder farmers. For example, insect pollination can increase the yield of commonly grown crops. Even autogamous crops can see considerable yield improvement, as demonstrated in a pollinator exclusion experiment performed by Elisante et al. (2020) on common beans. Pollinator-dependent crops are a source of nutrients for smallholder households, containing more micronutrients per unit area than non-pollinator-dependent crops (Mulungu et al. 2023). Furthermore, pollinator-dependent crops produce a significant portion of calories (19–26%), protein (19–28%), and iron (15–41%) as documented in the four sub-Saharan African countries of Ethiopia, Tanzania, Nigeria and Malai (Teklewold et al. 2021).

1.4 Soils in the East African Agricultural Context

Soils are an essential resource for millions of smallholder farmers across Africa. Yet in many parts of east Africa widespread soil degradation is present (Blake et al. 2018; Lohbeck et al. 2018). As is common for tropical soils, many East African soils are highly weathered and characterized by low pH, low cation exchange capacity (CEC), and limited phosphorus (P) availability due to sorption by aluminium (Al) and iron (Fe) oxides (Funakawa 2017). For example, 24% of soils in Western Kenya, fall below a pH of 5.6 a value which restricts maize productivity (Hijbeek et al. 2021).

East African soils are often low in nutrients and nutrient removals continue to exceed additions (Nyamasoka-Magonziwa et al. 2023). Most farmers have limited access to ways to build soil fertility. Although, a small minority of resource-endowed farms can access sufficient manure and chemical fertilizer to maintain soil fertility and crop productivity. Promotion of high input fertilizer and nutrient

management programs to these resource poor farmers will likely be unsuccessful due to insufficient capital or lack of availability (Chikowo et al. 2014). Fertilizer inputs alone have been shown to be insufficient to maintain yields. Inputs of organic matter, such as manure and plant biomass are crucial to maintain productivity (Vanlauwe et al. 2017). The inequity in nutrient use and availability results in soils that are highly heterogeneous (Vanlauwe et al. 2017). This heterogeneity extents to the farm level as well. For example, plots near households may receive preferential treatment from various organic inputs such as kitchen waste, manure and residues from crop processing (Vanlauwe et al. 2017; Namirembe et al. 2020).

In recent decades, using soil to sequester CO_2 for climate change mitigation has become a popular topic, becoming the focus of many highly cited research papers and drawing considerable funding (Paustian et al. 1997; Minasny et al. 2017). Despite significant research efforts, the capacity of soil to offset total anthropogenic greenhouse gas emissions is extremely varied; examples of estimates include around 1.5% (Janzen et al. 2022), 3-6% (Paustian et al. 1997), and 20-35% (Minasny et al. 2017).

Regardless of the sequestration potential, the soil's capacity to hold carbon is vast, several times greater than what exists in the atmosphere (IPCC 2023a) and management practices can have a large impact on soil carbon in agricultural soils (IPCC 2023a). However, tropical soils such as those in Kenya offer a more limited ability to sequester carbon due to low biomass inputs, warm climate, and rapid decomposition rates (Lal 2004). Furthermore, much of the limited soil carbon stocks of these soils have been lost following cultivation of the land. One study from a semi-arid region of Tanzania found that soil carbon content of cultivated land declined by over 50% following conversion from savanna to maize fields (Birch-Thomsen et al. 2007).

These losses of carbon are inevitable. Agricultural systems are export-oriented, aiming to export the greatest amount of usable net primary productivity from the system for human or animal consumption (Janzen et al. 2022). This includes grain, hay, wood products, fruits, vegetables and residues. In many

African maize-based systems, ‘cut and carry’ livestock feeding results in a concerted effort to remove crop residues from the system, resulting in heavily reduced carbon and energy inputs to the soil (Castellanos-Navarrete et al. 2015). This way of operation is alien to natural systems. However, implementing beneficial practices such as agroforestry can shift the system back toward a natural state and partially undo some of the losses in soil carbon (Namirembe et al. 2020).

Soil is especially important in an East African context as agriculture is a prominent source of livelihood. Over 40% of the population of Kenya is employed in the agricultural sector (KNBS 2025). Their livelihoods and food security are dependent on the soil and the ability of the soil to support plant growth. For this reason, halting soil degradation and promoting soil health is an important means of supporting human health, wellbeing and reducing poverty (Anikwe et al. 2026).

1.5 Farmer Managed Natural Regeneration

1.5.1 What is FMNR and How is it Practiced

Farmer managed natural regeneration (FMNR) is a practice where farmers engage in “restoring, managing and protecting non-planted trees and shrubs in agricultural landscapes, communal lands and rangelands” (Wanjira et al. 2020). Some farmers consider FMNR to be a revival and modification of traditional practices (Lohbeck et al. 2023). For example, traditional swidden systems, or “shifting agriculture,” incorporate elements of farmer managed natural regeneration through the natural regrowth that occurs during fallow periods. The long fallow period is analogous to FMNR implementation as they both attempt to restore natural vegetation to restore land functioning. This traditional swidden system has been practiced in the African continent for millennia (Finegan and Nasi 2004). However, increasing population densities have shortened rotations, leading to many of the regeneration benefits of swidden agriculture being lost (Finegan and Nasi 2004).

In more recent times, the practice of FMNR was formalized by Tony Rinaudo, an Australian agronomist working in Niger in the 1980s. He observed the vast potential to regenerate degraded and

deforested land by relying on existing tree stumps and soil seed banks (Rinaudo et al. 2021). The need for this alternative approach to reforestation stemmed from observations that tree planting, an expensive intervention, had poor tree survivability in arid environments. Tree planting efforts in Niger where Rinaudo worked in the 1980s had survival rates of only 20%, and this poor survival came with high upfront costs (Rinaudo et al. 2021). Generally poor survival rates can be attributed to drought stresses, weak species site matching, and livestock grazing in the seedling stage. Additionally, the success of these projects can vary significantly between project sites (Berhe et al. 2024). Finally, tree planting faces challenges from considerable post planting management requirements including watering and ongoing protection (Yiridomoh et al. 2024).

Tree planting on communal lands can face additional challenges, including, significantly lower tree survival rates compared to projects implemented by private individuals (Berhe et al. 2024). Tree planting on communal land can also cause conflict if groups such as pastoralists are prevented from accessing lands they previously were allowed to graze (Zhu et al. 2025).

FMNR has mostly been practiced in the Sahel region of Africa (i.e., Niger, Mali, Burkina Faso) (Binam et al. 2017; Chomba et al. 2020). While recent accountings of FMNR adoption are limited, a 2016 US Geological survey estimated there to be 15 million hectares of FMNR occurring in the seven west African countries included in the area of study (Rinaudo et al. 2021). Despite the focus on the Sahel, there are multiple examples of FMNR being promoted in Kenya (Ndegwa et al. 2017; Wanjira et al. 2020; Choge et al. 2024).

The implementation of FMNR is flexible and adapted to the needs of farmers. Generally, it relies on the living root systems of cut-down trees and on soil seed banks, which are often still present on overgrazed and deforested landscapes. The process of implementing FMNR begins with farmers identifying a degraded piece of land on which they wish to implement the practice. Farmers strategically manage existing woody vegetation by pruning multi-stemmed regenerating trees into one to three main

stems and removing lower branches to encourage vertical growth. Many of the trees that attempt to regenerate would otherwise take on a small bushy appearance because of repeated browsing by livestock and removal by farmers (Rinaudo et al. 2021). Additionally, some farmers may clear areas overgrown with thorny shrubs to open areas for future grazing or fodder production (Wanjira et al. 2020; Rinaudo et al. 2021).

A secondary component of FMNR involves managing livestock access (commonly cattle and goats in the project area of this thesis). Since many tree and shrub species in these arid environments contain thorns, branches from pruned vegetation are used to create barriers around FMNR sites. This stops uncontrolled grazing and protects regenerating plants from being immediately grazed. Farmers may still allow livestock to graze intermittently, especially during periods of droughts (Wanjira et al. 2020). FMNR management practices change over time. It transitions from a regeneration phase, where trees are pruned and regeneration is actively promoted, to a maintenance phase where grazing is controlled and wood products are harvested but tree densities are kept stable (Rinaudo et al. 2021). FMNR is most applicable in drier climates where traditional tree-planting methods often fail due to low and unpredictable rainfall (Wanjira et al. 2020; Rinaudo et al. 2021).

FMNR is a highly participatory practice. Methods are tailored to the specific landscapes and diverse needs of people within those landscapes (Rinaudo et al. 2021). This can make empirical studies of FMNR and comparisons across studies challenging. Definitions in development contexts vary (Rinaudo et al. 2021). In some cases, FMNR is promoted as an agroforestry practice with rows of crops being grown around regenerated trees (Reij and Garrity 2016). In these systems, species such as *Faidherbia albida* are often used. These species exhibit reverse phenology, losing its leaves in the rainy season rather than during the dry season (Reij and Garrity 2016). In other contexts, FMNR is promoted primarily to increase fodder production (Wanjira et al. 2020; Rinaudo et al. 2021). While FMNR usually focuses on restoring deforested and barren areas, it can also be used in contexts where woody encroachment becomes so dense as to restrict all access of grazing mammals from an area. In this scenario, FMNR involves clearing

woody undergrowth, pruning trees and opening areas for grasses to establish (Rinaudo et al. 2021). This preserves ecological functioning while allowing the farmer to economically benefit from the land.

Often FMNR is promoted alongside other practices to help accelerate the benefits. This may include enrichment planting of trees or grasses in areas where there is limited root stock or limited soil seed bank. Additionally, farmers may incorporate soil and water management techniques like terraces or swales (Rinaudo et al. 2021). Since firewood demand is a driver of deforestation in many areas, layering interventions such as introducing fuel efficient stoves can help reduce deforestation pressure and may increase willingness to preserve trees (Rinaudo et al. 2021).

1.5.2 Effects of FMNR on biodiversity

There is not a comprehensive accounting of the impacts of FMNR on biodiversity. In general, there is a lack of evidence on the effects of FMNR on biodiversity and ecosystem functioning (Chomba et al. 2020), underlining the importance of further study on this topic. Of the information that does exist, most studies focus on the impacts on trees. For example, Haglund et al. (2011) showed that FMNR increased tree richness in a project in Niger with FMNR farms having nine identified species compared to seven on non-FMNR farms. Similarly, Larwanou and Saadou, (2011) found increased tree diversity in field surveys in FMNR interventions. One study in Kenya, surveyed plant communities (including herbs, shrubs, and grasses) over four years. They observed higher species richness across different plant classifications in the FMNR plots, but this difference was confounded by the large differences in initial richness and declines in plant richness in the non-FMNR sites (Choge et al. 2024).

Other studies have highlighted the benefits that FMNR on tree density. Weston et al. (2015) observed that FMNR adopted within cropping systems increased tree densities from five trees ha^{-1} at baseline to 57 trees ha^{-1}. Focus group discussions revealed that tree densities were rapidly declining in the region prior to FMNR implementation (Weston et al. 2015). In another example from Niger, FMNR increased tree densities to 44 trees ha^{-1} compared to a baseline of 29 $ha^{-1.}$ (Haglund et al. 2011). The

increased tree densities from FMNR may help facilitate the restoration of degraded landscapes by facilitating increases in diversity and abundance of other plant species. Similar effects have been observed in non-FMNR restoration projects. Mullah et al. (2013) observed that the increased densities of certain tree species facilitated increases in the diversity and abundance of other plant species.

A common flaw observed in studies reporting tree density or abundance impacted by FMNR is that it is often unclear whether increases in tree densities resulted from natural regeneration within the FMNR system, or from other interventions such as tree planting (Chomba et al. 2020).

The impacts of plant communities mentioned above have potential further impacts on insect and mammal communities. Higher plant diversity is associated with higher arthropod abundance and diversity across multiple ecosystems (Schuldt et al. 2019). These authors also note that arthropod populations are mediated by the structural diversity of plant communities. Some anecdotal evidence indicates that FMNR increases wildlife diversity and abundance. A survey from a project in the Sahel stated that 79% of farmers perceived increases in wildlife diversity from FMNR (Cunningham and Abasse 2005).

The effects of FMNR on insect diversity and community structure have not yet been studied. However, the general practice of landscape restoration/regeneration is well-studied. These related practices can give insight into potential insect diversity/community changes resulting from FMNR adoption. Response of insects in cropping systems to natural and seminatural areas is complex. For example, an increase in surrounding shrubland cover can increase carabid abundance in maize but decreased their abundance in intercropped and bean fields (Vogel, Poveda, et al. 2023). The same authors found low amounts of shrubland cover were positively associated with increased natural enemies in beans. These interactions go against conventional agroecological wisdom – that diverse and functioning ecosystems possess greater abilities to self-regulate, resulting in natural enemies being better able to mitigate damage to cropping systems (Yadav et al. 2023). The impact becomes clearer when considering the overall effects on insects, not just how they benefit crop production. In a review of 31 studies,

Gonthier et al. (2014) found that incorporating natural and semi-natural areas into agricultural landscapes increased the richness and abundance of plant, vertebrate, and invertebrate communities. Other studies have highlighted the importance of trees in landscapes to support insect biodiversity. For example, In Malawi, farmland had roughly half the species richness as compared to surrounding woodlands (Vogel, Mayer, et al. 2023). In northern Tanzania, agroforestry has been shown to play an important role in supporting both insect abundance and diversity (Kingazi et al. 2025). Insect abundance during the dry season was twice as high in the agroforestry system compared to the non-agroforestry farms. Higher flower richness, plant richness, and overall plant abundance were determined to be drivers these higher abundances (Kingazi et al. 2025).

While insect diversity is an effective indicator for quantifying and assessing the impacts of land restoration (Watts and Didham 2006), including restoration approached such as FMNR , the effects of restoration on insect diversity are determined by several factors. For example, the recovery of insects in a restored environment is dependent on the connectivity of the landscape as in the distance to existing habitat (Watts and Didham 2006), as well as their mobility (Mortimer et al. 2002). Low-mobility insects will take longer to colonize restored habitats or may fail to recolonize (Mortimer et al. 2002).

The need to support biodiversity must be balanced with the need to provide livelihood opportunities and human well-being. Well-managed agroecological systems have highlighted the potential to create landscapes that provide benefits to humans while creating strong ecological systems that would not exist without active management. One example is the cork savannahs of the Iberian Peninsula and north-western Africa, which sustain more biodiversity compared to unmanaged portions of the landscape (Bugalho et al. 2011). Similarly, swidden agricultural practices can facilitate high levels of biodiversity under specific circumstances i.e. low population densities, by facilitating similarly diverse states of ecological succession (Finegan and Nasi, 2004). In the context of growing populations and improving living standards, which describes areas such as Kenya, excluding humans entirely from sections of land is

unlikely to be possible. Instead, methods such as FMNR must be employed that can support both ecological and human needs.

1.5.3 FMNR and Soil Health

Land use profoundly impacts soil organic carbon (SOC) and carbon dynamic of a soil system (Nyawira et al. 2021). Empirical evidence directly quantifying the impacts of FMNR on soil health, defined as the ability to provide ecosystem services and support plant growth for human benefit, remains limited and most studies rely on farmer perceptions (Kibru et al. 2021; Camara et al. 2023; Yiridomoh et al. 2024).

Across diverse study contexts, farmers have reported improvements in various aspects of soil health. Farmers in Ghana reported that FMNR helped support soil formation and control soil erosion. Farmers also reported increases in soil fertility (Yiridomoh et al. 2024). In Senegal, soil fertility improvement from FMNR was the most commonly perceived benefit by farmers, and soil moisture conservation was the third most commonly perceived benefit (Camara et al. 2023). In Ethiopia, farmers reported increased soil fertility and subsequently higher fodder and fruit availability from FMNR (Kibru et al. 2021). Additionally, observed benefits to crop yield and food security (Binam et al. 2015; Weston et al. 2015) suggest underlining improvements in soil conditions.

Substantial evidence supports the premise that increasing the density of trees increases soil carbon and above ground carbon stocks. Balima et al. (2020) compared carbon stocks of protected areas compared to agricultural lands and found higher carbon stocks in the protected areas. Tree density was the factor that had the greatest capacity to determine the carbon stocks of a system. Additionally, in a South African savanna, there was a general increase in ecosystem carbon (SOC plus biomass) in forests compared to grasslands. Most of these gains came from aboveground biomass (Coetsee et al. 2013). The relationship between increased trees and soil carbon is also observed in an agricultural context using FMNR. In the Sahel, higher soil carbon has been observed around trees in FMNR systems (Bayala et al.

2020). Carbon inputs from the trees themselves explained the higher soil carbon concentration surrounding trees, countering the theory that the higher carbon levels surrounding trees were simply due to trees being more likely to establish on more fertile sites (Bayala et al. 2006). Increases in soil carbon were attributed to litter and root inputs from the tree (Bayala et al. 2006). Trees also add nutrients to the surrounding soils from tree litter, and naturally concentrate animal droppings which can increase the productivity of the plants growing beneath and around trees (Belsky 1994).

More broadly, in a metanalysis covering multiple agroforestry practices in Sub-Saharan Africa, results showed that trees improved SOC and nitrogen concentrations. For example, parkland agroforestry systems increased nitrogen concentrations by 35.5% and increased SOC concentrations by 35.5% compared to a treeless control (Bayala et al. 2018).

Despite the observed relationship between tree density and carbon stocks, grasses are far more important in influencing SOC formation than trees and shrubs in African savannas and shrublands. A study in Kenyan semi-arid savanna (Wigley et al. 2020) observed that two decades of herbivore exclusion increased soil carbon in the 0-30 cm soil zone by 54%. Aboveground carbon stocks also increased. In the herbivore exclusion plots, C_4 (grass) derived carbon accounted for 71% of SOC. In the control plot, this number was 76%. Therefore, despite the significant increase in woody cover due to tree growth, most soil carbon was still derived from C_4 grasses. Other studies have found similar results on the importance of grassroots impacting soil carbon (February et al. 2020). FMNR increases grass and fodder production (Kibru et al. 2021) and therefore is expected to increase soil carbon. Future studies are required to understand the relative contributions between grasses and trees in overall carbon sequestration in FMNR systems.

1.5.4 Other FMNR Benefits

FMNR has been shown to increase annual incomes. The absolute increase can be quite small ranging from 46-56 USD per capita (Haglund et al. 2011) or 72 USD per farm (Binam et al. 2015). But,

even these small increases can be meaningful as this represents an increase in incomes of 18-25% (Haglund et al. 2011; Weston et al. 2015). Other accountings of the value created by FMNR have found larger increases. For example, Weston et al. (2015) used a social return on investment framework to quantify the annual value created by FMNR to be 655-887 USD per household. These benefits exceeded the implementation costs by 6:1 at the project end line and were predicted to be 43:1 ten years after project close. A large portion of the value created was in the stored value of trees (Weston et al. 2015). The same authors noted that this broader accounting still leaves out benefits such as higher education participation from children due to lower labour requirements to find firewood and fodder for livestock. FMNR can also increase incomes through diversification of farm products. Examples include honey, and shea butter production (Mensah et al. 2024) or through the sale of various forest products including fodder, firewood, resins, and wild foods (Kuyah et al. 2023).

FMNR enables the farmer to store value and resources within their land, which aids in increasing resiliency. Trees are a large component of this stored value (Weston et al. 2015) and FMNR adopters have higher tree densities compared to non-adopters (Haglund et al. 2011). FMNR also enables stockpiling fodder for future use through controlling livestock grazing (Brown et al. 2011). FMNR and the programs used to implement them have a been shown to increase leadership capacity in communities (Weston et al. 2015). This social capital can act as another form of resilience (Pretty and Ward 2001).

When FMNR is incorporated with annual crops, multiple studies have reported increased yields. One study that spanned several countries in the Sahel region found that crop productivity increased by 113-401 kg ha^{-1} depending on country assessed in response to increased tree densities in FMNR systems (Binam et al. 2017)**.** Other studies reported much smaller yield increases, ranging from 39 kg ha^{-1} to 70 kg ha^{-1} (Binam et al. 2015).

Several studies have also reported that FMNR had positive impacts on food security. One study reported that FMNR increased dietary diversity by 12-14% (Binam et al. 2015). A later study showed that

food consumption increased, as measured by a food consumption score, with higher tree densities (Binam et al. 2017). FMNR adoption is also associated with an increase in crop diversification (Haglund et al. 2011), with four crops being grown on average for FMNR adopters and three for non-adopters. The pods from several leguminous trees grown in FMNR systems, including *Faidherbia albida* and *Vachellia tortilis* are valuable as livestock feed and are sometimes sold (Kuyah et al. 2023). Vegetative portions of the tree are also valuable for livestock feed (Kuyah et al. 2023). Many of the native trees and shrubs promoted in FMNR are valued by farmers as traditional medicines (Rinaudo et al. 2021). Increases in food security may also be a result of the increased crop yields mentioned above, the provisioning of wild foods (Weston et al. 2015), microclimate modifications, improvements in soil fertility (Binam et al. 2017), and inputs from leguminous trees such as *Faidherbia albida* (Reij and Garrity 2016). However, FMNR does not always translate into increased food security. Haglund et al. (2011) observed no changes in months of food between FMNR adopters and non-adopters, despite observing other benefits of FMNR.

Additional benefits of FMNR include providing fuel wood and charcoal, honey, medicinal products, gums, dyes, resins, tannins, fodder, fruits, and timber (Wanjira et al., 2020; Rinaudo et al., 2021). This improved resource partitioning can help drive the income and food security listed above.

1.5.5 Factors Constraining FMNR Adoption

There are many scenarios where FMNR may be a poor fit. Some farms may face difficulties with illegal logging (Camara et al., 2023) and uncontrolled animal roaming (Kibru et al. 2021; Camara et al. 2023), which compromise tree generation. In circumstances where FMNR is adopted amongst cropland, the additional trees can hinder the use of animal traction, especially considering that FMNR provides limited choice over the location of trees if relying on regeneration from root stock (Camara et al. 2023). In high population areas, FMNR adoption may be challenged by limited land sizes and limited willingness to devote scarce land resources to the practice (Kibru et al. 2021). The biodiversity facilitated by FMNR may not always be perceived as positive. In one survey, farmers perceived an increased risk of snakes where FMNR was implemented (Weston et al. 2015).

Since FMNR relies on the natural availability of root stocks and seeds, its restoration potential is limited to contexts where these resources exist. As demonstrated by Lohbeck et al., (2020), a large portion of regeneration may come from seeds rather than rootstocks and the availability of these seeds for regeneration is determined in part by the distance to forested areas. This suggests that regeneration impacts may be reduced in areas with low tree densities in the surrounding landscape (Lohbeck et al. 2020).

Legal challenges can also act as barriers to FMNR adoption. In some areas there are restrictions in place that regulate and potentially prevent farmers pruning or thinning trees (Brown et al. 2011). Weak land tenure from informal settlement and lack of title deeds for land use rights disincentivizes any form of long-term investments in the productivity of the land (Ndegwa et al., 2017).

Communal FMNR practices may face significant challenges when they are misaligned with local land tenure systems and community dynamics (Kandel et al. 2021). For example, in Ghana, land designated for communal FMNR was not truly shared. Rather, certain households retained control over resource use rights. The lack of guaranteed access to resources deterred voluntary participation and instead, labourers expected payment. Ultimately the communal FMNR project was abandoned. These findings highlight that shared FMNR endeavours must get buy-in from all stakeholder groups who access the land. However, obtaining buy-in from migrating pastoralists may be particularly challenging. This has been a problem in FMNR and land management projects that implement restrictions on land access (Kandel et al. 2021; Zhu et al. 2025)

1.5.6 FMNR Research Gaps

Chomba et al., (2020) state that FMNR meets all the characteristics of an “iconic practice”, that is, a practice that has limited quantitative evidence for its claimed benefits and limited mechanistic understanding but is being widely promoted and adopted. The knowledge base of FMNR needs to ‘catch up’ to support the ongoing adoption. But establishing a sufficient knowledge base is challenging given the

diverse socio-economic and ecological contexts found across African countries implementing FMNR. Therefore, a great amount of research within each of these unique systems is required. Simultaneously, the African continent is critically understudied (Wagner 2020). More research on FMNR is needed to test and quantify the impacts of adoption.

Most research on FMNR has been focused on the Sahel region in Western Africa (Chomba et al. 2020). Based on a Web of Science search conducted in March 2026 only one peer reviewed study has specifically examined FMNR within Kenya in a Web of Science indexed journal (see Ndegwa et al. 2017). The evidence base of FMNR in Kenya largely comes from development-oriented program reports (e.g. World Vision projects), and several papers have been published using data from these projects (Wanjira et al. 2020; Choge et al. 2024; Oluoch et al. 2025). These contributions do provide valuable insights, but given the development-oriented priorities, they often prioritize implementation outcomes over controlled experiments and statistically robust approaches. Additionally, most of their focus remains on benefits to people rather than the environment. To date no studies could be identified that directly assess the impacts of FMNR on insect biodiversity. Understanding how FMNR impacts insect biodiversity is critical given the broad decline insect biodiversity and abundance and the lack of data within Africa (Wagner 2020). Research that focuses on the biophysical impacts most often is based on anecdotal evidence or from surveyed farmer perceptions (Camara et al. 2023; Yiridomoh et al. 2024). As a result, empirical evidence quantifying biophysical mechanisms such as changes in ground cover, soil function, and biodiversity, remains scarce in the region.

1.6 Conservation Agriculture

1.6.1 Context of the Practice

Conservation agriculture (CA) is a package of agricultural practices with three main pillars: minimum disturbance tillage, maintaining soil cover, and crop diversity (Montt and Luu 2020). Minimum disturbance tillage and crop diversity were already widely implemented in sub-Saharan Africa before the

development of CA as a formalized practice Intercropping and crop rotations are commonly practiced in many areas due to land constraints, necessity to reduce risk, and to grow food for personal consumption (Corbeels et al. 2015). Minimum disturbance cultivation is also common in many areas simply because the use of animal traction for tillage was not a traditional practice in regions besides Ethiopia. Intensive tillage systems were introduced in colonial projects or post-independence through agricultural development programs (Corbeels et al. 2015). A return to minimum tillage systems represents a return to traditional practices. Currently farmers may already practice minimum tillage due to a lack of equipment or animal traction. Historically, large-scale mulching (i.e., soil cover with plant material) has been the least observed of the three CA practices (Corbeels et al. 2015).

The three CA practices are often adopted in isolation from each other and rarely are the three practices adopted as a complete package. A survey of farmers from over 100 villages in nine countries in sub-Saharan Africa reported that approximately 80% of households had adopted one or more CA practices (Tambo and Mockshell 2018). However, the same study found that only 8% of surveyed farmers adopted all three CA principles (Tambo and Mockshell 2018).

1.6.2 Effects of CA on Biodiversity

Increasing plant diversity through crop rotations and intercropping is a key principle of CA. The increases in plant diversity can have observable impacts on insect diversity. A biodiverse seed mix in maize increased arthropod richness, density, and community structure both above ground and below ground (Norris et al., 2016). The plant diversity in systems to support insect diversity does not need to come from intentional sources. For example, weed cover can increase arthropod diversity but was neutral for abundance (Brandmeier et al., 2021).

It is well established that insect groups are positively impacted by implementing CA or individual principles of CA namely minimum disturbance, ground cover, and crop diversity. Vogel et al. (2023b) demonstrated an increase in pollinator visits to flowers as the number of agroecological soil management

practices increased. These practices included mulching, intercropping, and soil conservation tillage. In Germany, the abundance and diversity of arthropods and studied functional groups were higher in crop mixtures than in monocultures (Brandmeier et al. 2021). This included increases in abundance and diversity for pollinators and natural enemies (Brandmeier et al. 2021).

CA has been shown to have benefits for soil macro and mesofauna. A study in South Africa found that no-till increased abundance and diversity of earthworms (Mcinga et al., 2020). Furthermore, crop rotations positively affected earthworm diversity and density regardless of tillage practice. Earthworm parameters were correlated with positive soil health including reduced soil acidity, higher SOC, greater microbial biomass carbon, and increased soil moisture, highlighting the connection between healthy soils and healthy soil fauna. In another study, CA enhanced macrofauna taxonomic richness and mesofauna abundance. However, these results were more varied, and some treatments/trials had no significant impact (Ayuke et al. 2019).

While CA principles do appear to impact macrofauna biodiversity positively, adverse impacts are possible. In a study in the sub-humid tropics, Paul et al. (2015) used insecticide applications to exclude termites, the dominant macrofauna species in tropical agroecosystems (Lal 1988). Results showed that yields increasing by 34% in maize and 22% in soybeans. Therefore, pest damage, primarily from termites, outweighed any benefits provided by the presence of insects. Furthermore, Paul et al. (2015) observed no differences in soil quality (i.e., soil aggregation or carbon content) between the exclusion and control plots.

1.6.3 CA and Crop Yield

Conservation Agriculture (CA) has been promoted in Africa to offer simultaneous benefits towards achieving food security and environmental sustainability (Corbeels et al. 2015). When considering the benefits of food security, the impacts of CA range widely. Corbeels et al. (2020) conducted a meta-analysis on CA trials in sub-Saharan Africa. CA systems yielded only slightly higher than the

conventional ones, only four percent in the case of maize. Yield gains improved to eight percent for maize when multiple CA practices were combined. However, according to some surveys, farmers rarely adopt the complete CA package (Tambo and Mockshell 2018; Montt and Luu 2020). In contrast to the small yields outlined above, Entz et al. (2022) reported significant yield gains from CA adoption in East Africa. In Muranga County, Kenya, they observed yields increase from 77% to 180% of the county average (Entz et al. 2022). Food security can also be positively impacted by yield stability. CA has been shown to increase yield stability through intercrops (Madembo et al. 2020).

Yield gains from CA adoption are dependent on certain factors. It has been noted that CA often outperforms conventional systems to a larger extent in areas where water limits production (Steward et al. 2018; Corbeels et al. 2020). The impacts of climate change are expected to result in higher temperatures and increased rainfall uncertainty, potentially resulting in greater potential improvements from CA (IPCC 2023b). Additionally, herbicide use may be necessary to see these yield benefits (Corbeels et al. 2020). It is worth noting that herbicide use, especially in unregulated contexts, such as developing countries, can significantly impact human and environmental health (Ecobichon 2001).

1.6.4 Carbon and Soil Health Impacts of CA

CA systems are generally regarded as having positive impacts on SOC and so wide-scale adoption of CA in Africa could result in large quantities of carbon being sequestered. One estimate from a meta-analysis assessing the effects of SOC gains from CA suggested the sequestration potential was as high as 524 million tonnes CO_2 $year^{-1}$ (Gonzalez-Sanchez et al. 2019). Despite these optimistic claims, a review of individual studies shows that while CA can result in SOC gains, the results are not always consistent or impactful. This is reviewed below.

Malobane et al. (2020) found in a three-year study that the minimum soil disturbance treatment increased SOC by 15.83%. The significant increase in a relatively short period was attributed to substantial gains in labile organic carbon fractions. Labile organic carbon is characterized by its rapid

turnover and ability to be easily mineralized (Shen et al. 2021). On the other hand, a 13-year study in South Africa observed no change in total SOC under minimum soil disturbance. In the top 10 cm, increases in SOC were observed, and this brought shifts in soil properties, including higher Ca, P and organic N, but it reduced pH (Sithole and Magwaza 2019).

To add further complexity to the trends of SOC and CA, land management history can greatly impact SOC response. For example, in a long-term experiment in Kenya, Nyawira et al. (2021) assessed the impact of tillage, residue, manure, and fertilizer applications on SOC and observed that all treatments resulted in a decrease in SOC over time. However, the CA treatment had a lower rate of SOC decline. Land management history played a role in these results as the experiment was conducted in recently converted grass/shrub land, which had a high level of SOC prior to cropping.

Positive soil changes from CA can take time. Abdallah et al. (2021) noted that the most robust results for the impact of CA on macro and bio porosity occurred after 15-20 years with no significant benefits in the first five years. In another review, Steward et al. (2018) reported multiple benefits of CA but failed to see any effect of experiment length. The authors attributed this to a lack of statistical power, as only 4.1% of observations came from studies older than ten years. These results highlight the importance of long-term studies.

The time lag from CA adoption to tangible improvement may hinder farmer retention, resulting in them abandoning these practices before the benefits are seen (Giller et al. 2009). On the other hand, the significant improvements in soil health following CA adoption on farms in Kenya, Ethiopia and Tanzania were reported on fields that had been under CA for only 1-8 years (Entz et al., 2022). Thierfelder et al. (2015) stated that increases in soil characteristics and fertility over time are not just from compounding effects on the soil. They also are derived from increasing experience over time, allowing farmers to make better CA management decisions.

1.7 Determinants of Adoption

1.7.1 Typical Objectives

In agricultural development and the research that supports it, understanding the factors influencing the uptake and implementation of novel agricultural practices offers significant value to a variety of stakeholders. Specifically, it allows governments or NGOs to determine household and environmental contexts for which a practice is most suitable. Additionally, it helps assess what barriers may inhibit adoption of a practice (Teklewold et al. 2013). For example, if a project identifies poor land tenure as a variable limiting adoption (Saidou et al. 2021), the findings help policymakers and advocates identify the prerequisites needed for successful uptake of a practice. Alternatively, these types of studies can help highlight the need to find alternative interventions that are better suited for specific contexts. These types of analyses have been applied to many different agricultural contexts and practices (Daberkow and McBride 1998; Knowler and Bradshaw 2007). For farmers, this helps ensure that the information they receive is relevant to their context and their specific needs (Musafiri et al. 2022).

Previous research has examined farm and household characteristics such as education, awareness of environmental threats, age, and gender (Mazvimavi and Twomlow 2009; Mazvimavi and Twomlow 2009; Tibesigwa and Visser 2016; Foguesatto and Machado 2021; Saidou et al. 2021); biophysical characteristics, including distance to markets, soil fertility, plot slope, and rainfall (Assé and Lassoie 2011; Teklewold et al. 2013; Sabastian et al. 2014); financial characteristics, including on-farm income, off-farm income, credit access, and livestock ownership (Daberkow and McBride 1998; Fentahun and Hager 2010; Mutunga et al. 2024); and social capital, including membership in cooperatives, and participation in community meetings (Oduniyi et al. 2022; Hangamu et al. 2024). Many of these studies have focused specifically on CA (Foguesatto and Machado 2021; Knowler and Bradshaw 2007b; Mazvimavi and Twomlow 2009) and FMNR (Camara et al. 2023; Franzel 1999; Ndegwa et al. 2017). There is substantial variability in the parameters included across studies. Overall, no single factor

consistently predicts adoption. This inconsistency is typically attributed to the unique agricultural and socioeconomic contexts of different study areas (Knowler and Bradshaw, 2007).

1.7.2 FMNR

Adoption of FMNR is influenced by a diverse range of factors. Household resource endowment influences a farmer's choice to adopt FMNR. Higher resource endowment generally results in higher FMNR adoption (Camara et al. 2023). Land size is one of the most significant factors (Ndegwa et al. 2017). This has been observed by multiple studies (Binam et al. 2017; Ndegwa et al. 2017; Camara et al. 2023). The logic is that farmers with abundant land may be more likely to have spare land that they can take out of intensive production. Or they may be more interested in adopting a low labour, low capital solution to regeneration due to the large area they must manage. Other resource endowment-related factors that positively influence adoption, include using certified seed, having more livestock, more farm equipment, access to agricultural credit, and getting advice from technical services (Camara et al. 2023). Access to natural woodlands and distance to motorable roads have also been identified as variables that positively influenced tree protection (Ndegwa et al. 2017). Distance to motorable roads may also adversely affect tree conservation as roads also create improved access to markets and increase incentives to exploit tree resources, leading to observable drops in tree diversity (Abebe et al. 2013).

Governance also influences FMNR adoption. This may include how the farmer is included in tree species selection or the flexibility of practices suggested by a development agency (Chomba et al. 2020). Governance also considers land and tree tenure and if structures exist for grazing and conflict management (Chomba et al. 2020). The influence of land tenure was demonstrated by Camara et al. (2023), who showed that farmers who obtained their land through inheritance (i.e. possessing guaranteed rights to the land) adopted FMNR more frequently than less secure forms of land tenure (gift, loan, lease, etc.). In a survey in 9 sub-Saharan African countries, only 29% of farmers reported having a formal title or registration for their cultivated land (Tambo and Mockshell 2018). Therefore, limited land tenure may be negatively influencing adoption decisions of a large portion of the population

1.7.3 CA

Many studies have attempted to explain the factors influencing CA adoption. However, consistent trends across studies are difficult to identify. In a review of older studies Knowler and Bradshaw, (2007) highlighted that there were few consistent trends in what variables predicted adoption. They highlighted the potential of different methodologies and regional variation in driving results. For example, some variables such as more education and larger farm size often had positive impacts on adoption, but in other cases these same variables were insignificant or even negatively affected adoption (Knowler and Bradshaw, 2007).

Resource endowment is an important factor influencing the adoption of conservation agriculture and its component practices. This includes higher incomes (Foguesatto and Machado 2021), larger landholdings, and higher food security (Nata et al. 2014). This effect may be attributed to changes in farmers' risk preferences. Higher income may reduce risk aversion (i.e., willingness to try new crops or new practices) and increase farmers' capacity to mobilize resources (Asravor 2018). Conversely, lower resource endowment may place households in a poverty trap in which diminished risk tolerance limits their ability to adopt novel practices (Jumare et al. 2018).

Labour availability represents another important resource-related constraint affecting CA adoption. Access to labour and the ability to hire labour increases the likelihood of adopting conservation agriculture. This may be due to the intensive labour demands of CA. Despite the labour savings from reduced tillage adoption, increased time spent weeding reduces these labour-saving benefits (Montt & Luu, 2020). As suggested by Giller et al. (2009) and shown empirically by Montt & Luu (2020), women often bear the burdened by the increased labour demands. This is a result of social norms dictating that tillage is performed by men whereas weeding is primarily performed by women. Increased weed pressure associated with reduced tillage can be circumvented using mulch, another pillar of CA. However, mulch availability is another challenge limiting CA adoption (Giller et al. 2009).

Social capital can increase the adoption of CA. Social capital refers to the value derived from social relationships, trust, and community networks (Pretty and Ward 2001). Variables such as participation in community decisions, savings and loan groups, self-help groups, and women's livelihood groups all contribute to social capital. Social capital offers observable benefits such as support networks and trust (Pretty and Ward 2001). As a result, farmers participating in community groups are also more likely to adopt conservation agriculture (Knowler and Bradshaw, 2007; Ngwira et al., 2014; Oduniyi et al., 2022).

Beyond social and institutional factors, personal farmer characteristics can also influence adoption. As reported by Spurk et al. (2025), variables such as farmer innovativeness can have a larger impact than demographic or economic factors such as education level, age, and gender.

Finally, perceived environmental conditions and climate stresses impact adoption of CA. Some studies have examined the relationship between exposure to environmental disasters and adopting practices to crop rotation and minimal soil disturbance but not CA as a whole. Tanti & Jena (2023) found that farmers who perceived flood frequency to be increasing, promoted the adoption of crop diversification. Regarding droughts, perceived increases in drought frequency and direct personal experience with droughts had opposing effects on adoption, with perceiving droughts increasing adoption but personal experience decreasing adoption (Tanti and Jena 2023). In other contexts drought exposure can stimulate adoption of practices such as minimal soil disturbance (Etumnu et al. 2023).

CHAPTER 2. TRAINING, ENVIRONMENTAL AWARENESS, AND FOOD SECURITY DRIVE ADOPTION OF CONSERVATION AGRICULTURE AND FARMER MANAGED NATURAL REGENERATION IN A SEMI-ARID REGION OF KENYA

Authors: Andrew Enns, Sasha Loewen, Florence Nduku, Tayo Ajala, Mike Solomons, Martin Entz

Author contributions

Andrew Enns: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization, Methodology, Software, Validation

Sasha Loewen: Writing – review & editing, Conceptualization, Supervision, Software, Methodology

Florence Nduku: Writing - review & editing, Resources, Project administration

Tayo Ajala: Data curation, Project administration, Resources

Mike Solomons: Project administration, Resources, Funding acquisition

Martin Entz: Supervision, Funding acquisition, Writing – review and editing

2.1 Abstract

Nature-based solutions (NbS) have been proposed to address the combined challenges of climate change, land degradation, and low productivity in East African smallholder agricultural systems. However, adoption of NbS in Kenya remains limited, making it critical to understand the factors that influence uptake. We used logistic regression to identify predictors of adoption using survey data from smallholder farmers in Kitui and Makueni counties, Kenya. We examined adoption of conservation agriculture practices (crop diversification, minimal soil disturbance, and permanent soil cover), as well as farmer-managed natural regeneration and enrichment planting. Training emerged as the strongest predictor of adoption across all practices, highlighting the central role of knowledge transfer and extension. Exposure to environmental stressors, including drought, floods, and biotic pressures, was also positively associated with adoption. Higher incomes increased the likelihood of adoption, while food insecurity reduced it. Male-headed households were more likely to adopt, and the influence of community group participation varied by practice. These findings provide insight into the social and environmental

conditions shaping NbS adoption in semi-arid smallholder systems. By identifying key barriers and enabling factors, this study offers practical guidance for designing extension strategies and policies to support the wider uptake of agroecological practices in East Africa.

2.2 Introduction

Agricultural production in Kenya faces a challenging combination of threats. Food insecurity and poverty are common, especially in rural, arid areas. (FAO 2024). While global agricultural yields have steadily increased, yields in much of Africa have plateaued or declined (Wollburg et al. 2024; De Haas et al. 2025). This is in part due to widespread land degradation (Lal 2004; Moebius-Clune et al. 2011) and the impacts of climate change (Lesk et al. 2022). Nature-based Solutions (NbS) are interventions that conserve and restore managed and natural ecosystems, improving ecosystem services (Cohen-Shacham et al. 2016).

Prior to British rule in 1920, Kenyan farmers had developed agricultural practices adapted to their local context and implemented strategic, adaptive responses to local ecological and social conditions (McCann 1991). Agricultural extension policy during the colonial period (1920-1963) was practiced in a top-down fashion where it was assumed that general innovations were relevant to all farmers (Mukembo and Edwards 2016 Dec 1). In the post-colonial era, and particularly by the 1990s, there were significant shifts in Kenya to a more farmer-focused approach (Mukembo and Edwards 2016 Dec 1). More recently, participatory approaches have become a popular form of agriculture development and extension work (Mukembo and Edwards 2016 Dec 1; Entz et al. 2022), and this shift toward farmer-focused, context-specific approaches requires understanding how the unique context of farmers shapes their individual interactions with proposed technologies (Knowler and Bradshaw 2007b).

Conservation agriculture (CA), farmer managed natural regeneration (FMNR) and enrichment planting, are NbS being promoted in Kenya and other East African countries. CA consists of three practices: crop diversification, minimal soil disturbance, and permanent soil cover (Corbeels et al. 2015).

In the context of this project, crop diversification often took the form of intercropping, but crop diversification may also include lengthening crop rotations. Minimal soil disturbance is an alternative to intensive cultivation. Farmers either manually create individual planting stations or use a ripper, a device pulled using animal traction (or in rarer cases tractors) to help break up soil without turning it over, the farmer then plants into the furrow that is created. Finally permanent soil cover involves covering the soil with crop residues or other biomass sources, such as grasses from field margins (Corbeels et al. 2015).

Numerous benefits and challenges of CA adoption have been identified. CA has been reported to improve soil health (Sithole and Magwaza 2019; Malobane et al. 2020; Mcinga et al. 2020), local biodiversity (Norris et al. 2016; Mcinga et al. 2020; Vogel, Mkandawire, et al. 2023), and improve food security (Corbeels et al. 2015; Madembo et al. 2020; Entz et al. 2022). One challenge with CA adoption is plant biomass availability for soil cover (Bouwman et al. 2021). In areas with low biomass production, farmers face a decision of how to allocate plant material between mulching, livestock feed (Giller et al. 2009; Valbuena et al. 2012; Thierfelder et al. 2015), cooking fuel, and construction materials (Valbuena et al. 2012). A second barrier is that CA benefits often take multiple years to accrue. A meta-analysis found that soil health benefits were only observed after 15-20 years (A.M. Abdallah et al. 2021). Therefore, the upfront costs of reduced animal feed (Valbuena et al. 2012), and increased labour demands (Montt and Luu 2020) can take years to be recovered. Additionally, in absence of payment for ecosystem services programs, farmers only experience a portion of the ecological benefits they generate. Many benefits occur at scales beyond the farmer's field and are realized by different stakeholders. These impacts include reduced erosion (Corbeels et al. 2015), which can lower sedimentation of waterways; carbon sequestration (Gonzalez-Sanchez et al. 2019); and reduced runoff (Corbeels et al. 2015) leading to reduced downstream flooding. Thus, it is the surrounding community that also experiences the benefits (Knowler and Bradshaw 2007b). In the absence of government or non-governmental organization support, the farmer bears the full cost of implementation, while seeing only a portion of the benefits, and only after several years.

FMNR involves protecting and enhancing trees and shrubs in agricultural landscapes, while restricting livestock grazing (Wanjira et al. 2020). Existing trees are protected through physical barriers or community bylaws and are pruned to promote growth that is out of reach to livestock. Additionally, through enrichment planting, new and diverse local tree and grass species are added (Wanjira et al. 2020). Since the promotion of FMNR began in the 1980s, adoption has been widespread across much of the African Sahel (Kuyah et al. 2023). A 2019 estimate suggested that in Niger alone FMNR has been adopted on over seven million hectares (Garrity and Bayala 2019). Positive effects of FMNR have also been reported in Kenya (Nyanhanda et al. 2024). FMNR has been shown to improve soil health parameters such as soil organic carbon (Bayala et al. 2020; Kuyah et al. 2023), and biodiversity (Haglund et al. 2011; Nyanhanda et al. 2024). Additional benefits arise from the provisioning services provided by the increased tree abundance, which increase timber, fruit, fodder, firewood, resin, and charcoal availability (Haglund et al. 2011; Kuyah et al. 2023). FMNR can also act as an opportunity for fodder stockpiling (Brown et al. 2011), and can increase dietary diversity (Binam et al. 2015). Yet, many of the benefits of FMNR remain insufficiently quantified (Chomba et al. 2020).

Adoption of FMNR faces several challenges, including illegal logging, uncontrolled animal roaming, difficulties using animal traction amongst trees and shrubs, and restrictions on grazing (Camara et al. 2023). Legal barriers to FMNR include restrictions on tree management and cutting (Brown et al. 2011) and uncertainties around land tenure limiting long term investments in the land (Ndegwa et al. 2017).

Many studies have explored the factors that influence farmers' decision-making processes when adopting a new practice. Previous research has examined farm and household characteristics such as education, awareness of environmental threats, age, and gender (Mazvimavi and Twomlow 2009; Tibesigwa and Visser 2016; Foguesatto and Machado 2021; Saidou et al. 2021); biophysical characteristics, including distance to markets, soil fertility, plot slope, and rainfall (Assé and Lassoie 2011; Sabastian et al. 2014; Teklewold et al. 2021); financial characteristics, including on-farm income,

off-farm income, credit access, and livestock ownership (Daberkow and McBride 1998; Fentahun and Hager 2010; Mutunga et al. 2024); and social capital, including membership in cooperatives, and participation in community meetings (Oduniyi et al. 2022; Hangamu et al. 2024). Many of these studies have focused specifically on CA (Knowler and Bradshaw 2007b; Mazvimavi and Twomlow 2009; Foguesatto and Machado 2021) and FMNR (Franzel 1999; Ndegwa et al. 2017; Camara et al. 2023). There is substantial variability in the parameters included across studies. Overall, no single factor consistently predicts adoption. This inconsistency is typically attributed to the unique agricultural and socioeconomic contexts of different study areas (Knowler and Bradshaw 2007b). Therefore, the objective of this study is to identify which factors influence the adoption of CA and FMNR within a modern Kenyan context. Collectively, these results have broad policy implications for designing effective intervention strategies and improving studies that aim to monitor intervention effectiveness.

2.3 Methods

2.3.1 Site Description

This study uses data generated from the Nature+ program, a Canadian Foodgrains Bank development project funded by Global Affairs Canada (Global Affairs Canada 2017 Jan 21). Local organizations partner with the Canadian Foodgrains Bank to implement Nature+ interventions. Four project partners operating in four Kenyan wards are the focus of this study (Figure 2-1). These partners are Adventist Development and Relief Agency Kenya (ADRA), operating in Kanyangi Ward; the National Council of Churches of Kenya (NCCK), operating in Athi Ward; Utooni Development Organization (UDO), operating in Kikumbulyu North Ward; and Fadhili Trust (Fadhili), operating in Kikumbulyu South Ward.

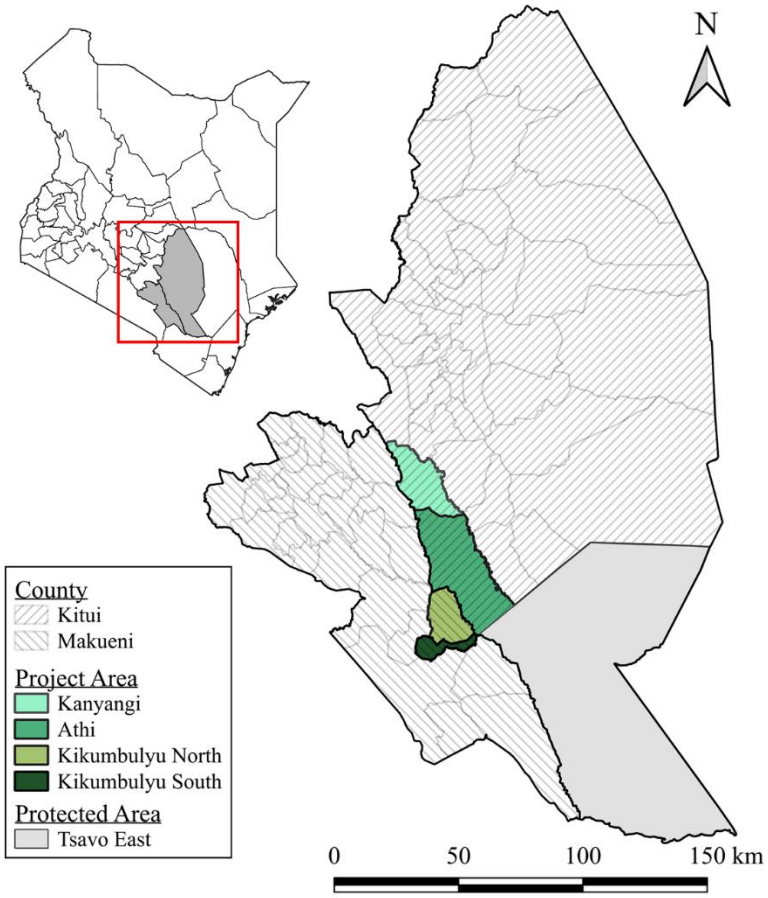


Figure 2-1. The smaller image shows Kitui and Makueni counties highlighted within Kenya. The larger image highlights the project area with in the two counties.

Contextual information was synthesized from internal reports produced by implementing partners. These documents reveal several similarities across the four study locations. Partner reports consistently note that women are often excluded from decision-making. Land ownership is predominantly held by men, and stigma surrounding women's land ownership persists. Within farming systems, women provide much of the labour but are excluded from most monetary gains. Reports from ADRA indicate that women frequently lead environmental conservation efforts but are constrained by cultural norms that limit their ability to make management decisions (partner project documents).

The types of landscape degradation identified in the partner reports were consistent between the four communities/partners and included deforestation, soil erosion, and gully formation. Reported drivers

of this degradation included poor soil management practices such as ploughing, free grazing, over-grazing, clearing trees for charcoal production, and land-use changes associated with expanding cultivated and inhabited areas (partner project documents). The thirty-year average rainfall was 659 mm $year^{-1}$ at the ADRA project location, 564 mm $year^{-1}$ at NCCK, 602 mm $year^{-1}$ at UDO and finally 573 mm $year^{-1}$ at Fadhili (Funk et al. 2015). The mean annual temperature was nearly identical across all locations, averaging 24 °C (Hajar and Basu 2021).

2.3.2 Survey

The survey was a standardized questionnaire designed by program staff in consultation with local partners. The survey was translated into local languages, and questions were adapted to ensure that responses were relevant and understandable to participants. This study used anonymized secondary survey data collected from smallholder farmers in Kenya. Ethical approval for data collection was obtained by the implementing organizations, and all data were anonymized prior to analysis. Research and partner staff attended a five-day baseline training workshop on the survey methodologies and an orientation to the SurveyCTO software used for data collection. This included implementing partners of the Nature+ project as well as Canadian Foodgrains Bank and University of Manitoba staff. The surveys were administered between December 7, 2023, and January 5, 2024. Approximately 10% of Nature+ project participants were selected, through random sampling stratified by partner, to participate in the survey. The survey consists of baseline data, collected prior to the activities of the project. The survey included 1,529 Kenyan participants with complete data, distributed across UDO (N = 374), ADRA (N = 349), NCCK (N = 396), and Fadhili (N = 410). From this dataset, 18 variables were selected for analysis (

Table **2-1**). The rationale for selecting these variables is outlined below.

Months food insecure was included to assess the applicability of these practices for food insecure individuals who may be concerned with immediate solutions rather than ones with a long term focus (Nata et al. 2014). Annual income was included to assess the applicability of these NbS to low-income farmers, a demographic that may struggle to adopt improved practices (Teklewold et al. 2013). We included livestock income because livestock compete for crop residues, limiting the mulch available for soil cover (Giller et al. 2009). We used this indirect measurement of livestock ownership, as no direct measure was available. Limited labour for agriculture was included as a variable in the analysis because NbS can alter both upfront and ongoing labour requirements (Montt and Luu 2020). Exposure to floods, droughts and biotic stresses was included to evaluate farmers' responses to environmental disasters. These NbS are often proposed as ways to increase resilience to these same shocks (McCarthy et al. 2021). Perceiving changing weather patterns assessed if farmers are choosing NbS in response to perceived changes in climate, a relationship documented by other authors (Makate et al. 2017). Gender of the household head is often included in similar studies and varies by location (Twyman et al. 2014). Additionally, project partners indicated that women were often the ones engaged in adopting these practices yet faced cultural barriers that limited adoption (unpublished report); we wished to test these perceptions. Participation in community decision-making, savings and loan groups, self-help groups, and women's livelihood groups were included as an assessment of social capital. Together, these variables assess how influential community members and community groups shape adoption. Previous studies have highlighted the importance of social connections (Pretty and Ward 2001) and community groups in the adoption of new practices (Hangamu et al. 2024). Receiving money or credit, tools or new technology, and seeds or seedlings assess the impacts of external support. Receiving training (and information) was included to assess whether lack of knowledge or training constrained adoption. This may have include information received during project onboarding. Finally, we included the four project partners as a variable to control for location effects.

Table 2-1. List of the independent variables, description, and types of variables which were included in the logistic regression models. Binary variables were yes or no (or male/female), number of months food insecure ranged from 0 to 12, and annual income was log transformed.

Variable	Description	Variable type
Months food insecure	The number of months food insecure between January and December 2023.	Number of months
Annual income	Average annual income in Kenyan shillings as estimated by the household.	Log transformed
Livestock income	Participant responded stating livestock were a source of income.	Binary
Limited labour for agriculture	Participant responded that limited labour was a challenge for agricultural production.	Binary
Experienced floods	Participant experienced disastrous flooding in the past five years.	Binary
Experienced droughts	Participant experienced disastrous droughts in the last five years.	Binary
Experienced biotic stresses	Participant experienced disastrous crop pests or diseases in the last five years.	Binary
Perceived changes in weather patterns	Participant noted experiencing changing weather patterns.	Binary
Male household head	The household head was reported as male.	Binary
Participation in community decisions	Participant responded that they had the knowledge, skills, and confidence to participate in community decisions surrounding land and water use.	Binary
Savings and loan group	Participant or family member is a member of a savings and loan group.	Binary
Self-help group	Participant or family member is a member of a self-help group.	Binary
Women's livelihood group	Participant or family member is a member of a women's livelihood group.	Binary
Received money or credit	Participant reported receiving money or credit as support to adopt NbS.	Binary
Received tools or new tech	Participant reported receiving tools or new technology as support to adopt NbS.	Binary
Received seeds or seedlings	Participant reported receiving seeds or seedlings as support to adopt NbS.	Binary
Training for: i. Crop diversification ii. Minimal soil disturbance iii. Permanent soil cover iv. FMNR v. Enrichment planting	Participant reported receiving information or training for a specific NbS.	Binary
ADRA	Location dummy variable	Binary
NCCK	Location dummy variable	Binary
UDO	Location dummy variable	Binary
Fadhili	Location dummy variable	Binary

2.3.3 Statistical Analysis

Logistic regression was used to estimate the determinants of adoption. Based on the conceptual framework of Funk et al. (2020) we assume that a farmer will adopt a given practice when the utility associated with adoption exceeds the utility associated with non-adoption. For each NbS, the farmer may choose either to adopt or not adopt the practice; therefore, a logistic (logit) model is appropriate, where 1 indicates adoption and 0 indicates non-adoption (Funk et al. 2020). The model can be conceptualized as follows:

$$y_{ij}^{*} = X_{ij}\beta_j + \varepsilon_{ij},$$

where y_{ij}^{*} is the unobserved net benefit to household *i* from adopting NbS *j*. X_{ij} is a vector of explanatory variables associated with adoption, as summarized in Table 2-1, and β_j is the corresponding vector of coefficients. The error term is denoted as ε_{ij}. We do not measure the net benefit of adopting directly but observe whether adoption occurs. Accordingly, the observed adoption outcome y_{ij} is defined as:

$$y_{ij} = \begin{cases} 1 \;\; if \;\; y_{ij}^{*} > 0 \\ 0 \;\; if \;\; y_{ij}^{*} \leq 0. \end{cases}$$

Under this specification, the probability that household i adopts NbS j is given by:

$$Prob\big(y_{ij} = 1 \,\big|X_{ij}) = \; \Lambda(X_{ij}\beta_j).$$

The probability of household *i* adopting NbS *j* is equal to the logistic function, denoted by $\Lambda(\cdot)$, evaluated at $X_{ij}\beta_j$. It maps the linear combination of explanatory variables into a probability bounded between zero and one. This implies that adoption probabilities increase as the expected net benefit of adoption rises, while remaining bounded between zero and one. The logistic specification allows adoption decisions to depend on observed household characteristics, reflecting the presence of unobserved factors influencing adoption behavior.

All statistical analyses were performed in R version 4.5.1 (R Core Team 2025). Annual income values were log-transformed to meet assumptions of the model. A logistic regression model was created for each of the five dependent variables individually using 18 explanatory variables (

Table **2-1**). McFadden Pseudo-R^2 values were calculated for each model because this R^2 is tolerant of varying base rates (i.e. the proportion of 1 and 0 responses for the dependent variable) (Menard 2000).

To increase interpretability for binary terms, average marginal effects were calculated as discrete changes in predicted probabilities calculated as the sample-average difference in predicted probability when the variable is set to one versus zero, while other covariates are held at their observed values. The logistic function is nonlinear and average marginal effects are dependent on all other model coefficients, therefore to quantify uncertainty for visualizations, we used parametric simulations (1,000 draws) using the MASS package (Venables and Ripley 2002), following standard approaches for non-linear models to generate 95% confidence intervals (King et al. 2000).

Separate methods were used for annual income and months food insecure. Using the logistic regression model outputs, we calculated sample-average predicted probabilities of adoption at defined intervals. For income, we first created a sequence of income values ranging from 10,000 Kenyan shillings (KES; 5th percentile) to KES 500,000 (99th percentile) in increments of KES 10,000. These values were then log-transformed, and the models were used to calculate the predicted probabilities for each income increment, holding all other covariates at their observed values and averaging predictions across households. To quantify uncertainty, 95% confidence intervals were calculated using non-parametric bootstrapping (1,000 iterations) (Mooney and Duval 1993). Then the model was refitted and predicted probabilities recalculated at the specified income levels. Uncertainty was summarized using the 95% confidence intervals of the resulting bootstrap distribution. The calculated predicted probabilities were then graphed over the income range for each model. For months of food insecurity, predicted probabilities were calculated for zero–12 months on one-month increments using the same averaging procedure. The calculated predicted probabilities were then graphed over all month increments for each model.

We tested for multicollinearity concerns in our models using a correlation matrix using *ggplot2* (Wickham 2016) and by calculating VIF values using the *car* package (Fox and Weisberg 2019). No

problematic variables were detected (Figure A-1; Table A-1), when applying commonly cited critical values, namely correlation values over 0.7, VIF values over 10 (Yoo et al. 2014).

2.4 Results

2.4.1 Summary Statistics

The mean survey response was calculated for each dependent and independent variable across the entire dataset and for each project partner (Table 2-2). Adoption rates differed for the five NbS. Crop diversification was adopted by 42% of participants; minimal soil disturbance by 29%; and permanent soil cover by 19%. The least adopted NbS was FMNR with just 3% of farmers reporting adopting the practice. In contrast enrichment planting was the most adopted NbS, practiced by 51% of farmers. We observed considerable variability in mean responses between partners for these dependent variables (Table 2-2).

Across all locations, average annual household income was KES 79,820 and the median was KES 50,000. Nearly half of participants in the survey had some form of livestock income. Agricultural labour shortages were reported on 13% of farms. On average the surveyed farmers experienced 4.4 months of food insecurity in the past 12 months. Sixteen percent of farmers experienced flooding in the past five years, 84% of farmers reported experiencing drought and 31% of farmers experienced biotic stresses including crop pests and diseases (Table 2-2).

Forty-eight percent of households reported perceiving changing weather patterns. Male-headed households accounted for 74% of surveyed households. Seventy-six percent of surveyed individuals indicated they had the knowledge and confidence to make community decisions regarding land and water use. Respondent participation in savings and loan groups was 41%, participation in self-help groups was 53%, and participation in women's livelihood groups was 17%. Eight percent of households had received money or credit to support NbS adoption; 18% had received tools or new technology to support adoption; and 31% had received seeds or seedlings. Finally, among surveyed farmers, 36% had received some form

of training on crop diversification, 27% for minimal soil disturbance, 17% for permanent soil cover, 4% for FMNR, and 44% for enrichment planting (Table 2-2).

Table 2-2. Mean survey response (% 'yes') ± SD in the aggregated data (referred to as 'Kenya') and by individual partner. Dependent model variables are listed in bold. All variables are a binary response of yes or no (coded as 1 or 0), except for annual income and months food insecure. Income values in Kenyan shillings (KES) are shown untransformed for interpretability.

Characteristic	Kenya	ADRA	UDO	NCCK	Fadhili
Crop diversification	0.42 ± 0.49	0.41 ± 0.49	0.53 ± 0.50	0.61 ± 0.49	0.13 ± 0.34
Minimal soil disturbance	0.29 ± 0.45	0.24 ± 0.43	0.23 ± 0.42	0.54 ± 0.50	0.15 ± 0.36
Permanent soil cover	0.19 ± 0.39	0.24 ± 0.43	0.25 ± 0.43	0.07 ± 0.26	0.19 ± 0.39
FMNR	0.03 ± 0.18	0.03 ± 0.18	0.02 ± 0.13	0.08 ± 0.27	0.01 ± 0.10
Enrichment planting	0.51 ± 0.50	0.69 ± 0.46	0.35 ± 0.48	0.63 ± 0.48	0.42 ± 0.49
Months food insecure	4.43 ± 2.63	4.24 ± 2.78	3.56 ± 2.19	4.79 ± 2.26	5.13 ± 2.95
Log of annual income	10.75 ± 1.19	10.17 ± 1.49	10.96 ± 1.08	11.26 ± 0.73	10.58 ± 1.09
Annual income	*79,820 ± 127,346*	*53,931 ± 102,567*	*76,672 ± 186,230*	*85,393 ± 94,885*	*10,1528 ± 88,948*
Livestock income	0.47 ± 0.50	0.59 ± 0.49	0.44 ± 0.50	0.57 ± 0.50	0.32 ± 0.47
Limited agricultural labour	0.13 ± 0.33	0.17 ± 0.38	0.18 ± 0.38	0.12 ± 0.32	0.05 ± 0.22
Experienced floods	0.16 ± 0.36	0.32 ± 0.47	0.13 ± 0.34	0.05 ± 0.21	0.14 ± 0.35
Experienced droughts	0.84 ± 0.37	0.91 ± 0.28	0.92 ± 0.27	0.92 ± 0.27	0.61 ± 0.49
Experienced biotic stresses	0.31 ± 0.46	0.60 ± 0.49	0.19 ± 0.39	0.13 ± 0.34	0.33 ± 0.47
Perceived changes in weather patterns	0.48 ± 0.50	0.63 ± 0.48	0.25 ± 0.43	0.68 ± 0.47	0.40 ± 0.49
Male household head	0.74 ± 0.44	0.79 ± 0.41	0.82 ± 0.38	0.59 ± 0.49	0.75 ± 0.43
Confidence community decision making	0.76 ± 0.42	0.90 ± 0.30	0.75 ± 0.43	0.74 ± 0.44	0.68 ± 0.47
Saving + loan group	0.41 ± 0.49	0.55 ± 0.50	0.14 ± 0.35	0.63 ± 0.48	0.36 ± 0.48
Self-help group	0.53 ± 0.50	0.59 ± 0.49	0.48 ± 0.50	0.66 ± 0.48	0.39 ± 0.49
Women's group	0.17 ± 0.38	0.11 ± 0.32	0.03 ± 0.17	0.28 ± 0.45	0.25 ± 0.43
Received money or credit	0.08 ± 0.27	0.04 ± 0.20	0.17 ± 0.38	0.06 ± 0.24	0.05 ± 0.21

Received tools or new tech	0.18 ± 0.38	0.24 ± 0.43	0.09 ± 0.28	0.34 ± 0.48	0.06 ± 0.24
Received seeds or seedlings	0.31 ± 0.46	0.42 ± 0.49	0.48 ± 0.50	0.22 ± 0.41	0.13 ± 0.34
Training for crop diversification	0.36 ± 0.48	0.29 ± 0.45	0.48 ± 0.50	0.59 ± 0.49	0.09 ± 0.29
Training for minimal soil disturbance	0.27 ± 0.45	0.20 ± 0.40	0.22 ± 0.41	0.56 ± 0.50	0.12 ± 0.33
Training for permanent soil cover	0.17 ± 0.38	0.22 ± 0.41	0.21 ± 0.41	0.13 ± 0.34	0.13 ± 0.34
Training for FMNR	0.04 ± 0.20	0.02 ± 0.13	0.01 ± 0.11	0.11 ± 0.31	0.03 ± 0.18
Training for enrichment planting	0.44 ± 0.50	0.55 ± 0.50	0.34 ± 0.47	0.58 ± 0.49	0.33 ± 0.47

2.4.2 Logistic Regression

For the following results full output tables for logistic regression models and calculated marginal effects can be found in Appendix A (Table A-2; Table A-3).

Economic variables impacted adoption. Higher annual income significantly ($p < 0.05$) increased the predicted probability of adopting crop diversification (Figure 2-2). Individuals with an annual income of KES 10,000 had a 37.9% probability of adopting crop diversification. At an annual income of KES 100,000 the probability increased to 43.3% and at KES 500,000 it increased to 47.3%. Higher annual income also significantly increased the predicted probability of adopting FMNR. At a household income of KES 10,000 the probability of adopting was 1.3%; at KES 100,000, it was 4.1%, and at KES 500,000, it was 8.5% (Figure 2-2; Table A-3). Months food insecure significantly reduced the predicted probability of permanent soil cover adoption. At zero months of food insecurity, the probability of adopting was 22.3%. At 12 months of food insecurity, the probability of adopting was 13.6%. Months food insecure also reduced the predicted probability of adopting FMNR (Figure 2-3). The probability of a farmer adopting was 5.1% at zero months of food insecurity, but at 12 months it decreased to 1.3% (Figure 2-3; Table A-4).

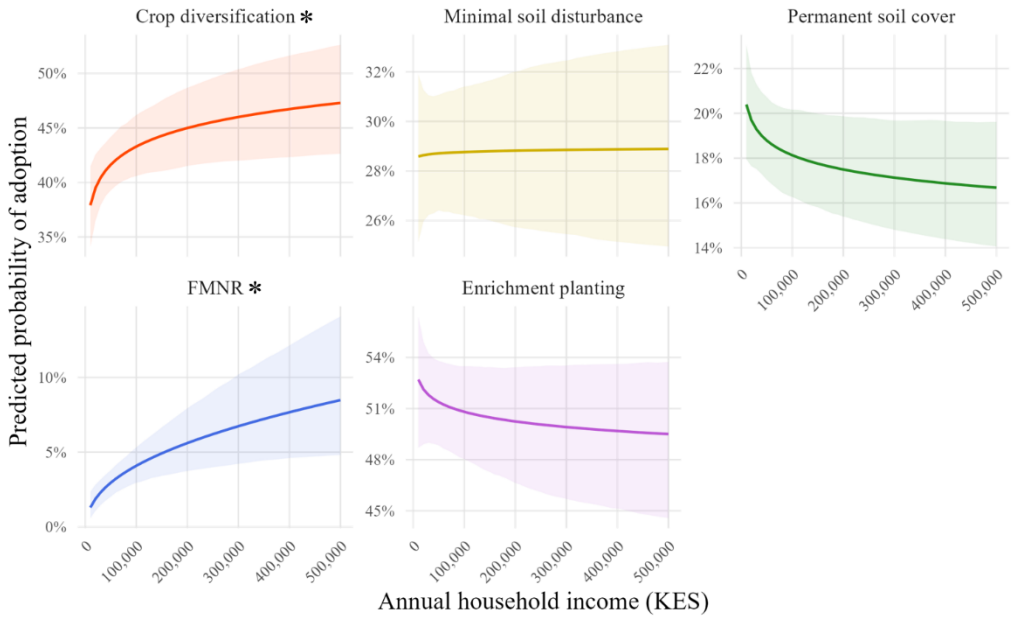


Figure 2-2. Calculated predicted probabilities of adopting five nature-based solutions based on annual income. Predicted probability was calculated in KES 10,000 increments ranging from KES 10,000–500,000. Lighter bands represent 95% confidence interval (bootstrapped, n= 1,000). Significance is based on the logistic regression results presented in Table A-2. Significance is indicated by an asterisk (*) near the top of the graphs. Note that y-axis scales differ between practices.

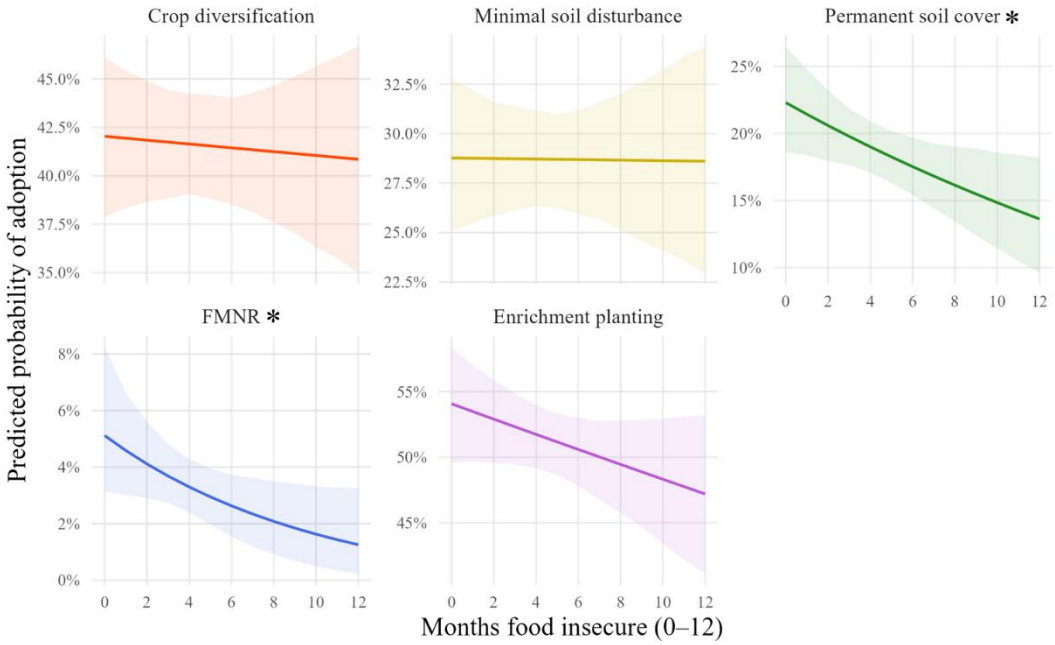


Figure 2-3. Calculated predicted probabilities of adopting five nature-based solutions based on months 0-12 of food insecurity. Lighter bands represent 95% confidence intervals (bootstrapped, n = 1,000).

Significance is based on the logistic regression results presented in Table A-2. Significance is indicated by an asterisk (*) near the top of the graphs. Note that y-axis scales differ between practices.

Livestock income significantly increased the probability of adopting permanent soil cover by 3.5 percentage points (Figure 2-4). Limited labour for agriculture significantly increased the probability of adopting crop diversification by 8.9 percentage points and permanent soil cover by 5.9 percentage points (Figure 2-4).

Environmental variables affected adoption. Experiencing floods increased adoption of all NbS except for FMNR. For example, flood exposure increased adoption of crop diversification and minimal soil disturbance by 11 and 10.5 percentage points, respectively. Experiencing droughts significantly increased adoption of crop diversification and enrichment planting by 7.4 and 7 percentage points respectively. Experiencing biotic stresses significantly increased adoption of crop diversification by 13.7 percentage points. Perceiving changing weather patterns significantly increased the probability of adopting minimal soil disturbance by 5.4 percentage points (Figure 2-4).

Social variables affected adoption. The gender of the household head had significant effects. Having a male headed households increased the probability of adopting permanent soil cover by 3.8 and enrichment planting by 4.4 percentage points (Figure 2-4). Community group participation had inconsistent impacts on adoption. Savings and loan group participation reduced the predicted probability of adopting both minimal soil disturbance and enrichment planting by 5.4 and 4.3 percentage points respectively. Participation in women's groups significantly increased the probability of adopting crop diversification and minimal soil disturbance by 7.3 and 6 percentage points, respectively. Both self-help groups and women's livelihood groups were associated with marginally significant ($p < 0.1$) increases in enrichment tree planting adoption (Figure 2-4).

Variables related to directly supporting farmers affected adoption. Receiving money or credit significantly increased the probability of adopting permanent soil cover by 7.6 percentage points. Receiving tools or new technology significantly increased the probability of adopting minimal soil

disturbance by 6.8 percentage points. Receiving seeds or seedlings significantly increased the probability of adopting minimal soil disturbance, permanent soil cover, and enrichment planting by 6.6, 4.5 and 8.7 percentage points, respectively (Figure 2-4). Training was highly significant in predicting increases in adoption of all five NbS. For crop diversification, receiving training increased the predicted probability of adoption by 53.9 percentage points, representing an increase from 21.8% to 75.7%. For minimal soil disturbance, the probability of adoption increased by 52.6 percentage points. In the absence of training, the predicted probability of minimal soil disturbance adoption was 13.5% but increased to 66.1% when training was received. Probability of adopting permanent soil cover increased by 55.8 percentage points, rising from 8.3% to 64.1%. The probability of adopting FMNR increased by 35.6 percentage points, from 1.4% to 37.0%. Finally, the probability of adopting enrichment planting increased by 60.1 percentage points, rising from 25.7% to 85.8% (Figure 2-4). McFadden R^2 values ranged from 0.358 in the minimum soil disturbance model to 0.462 in the FMNR model (Figure 2-4).

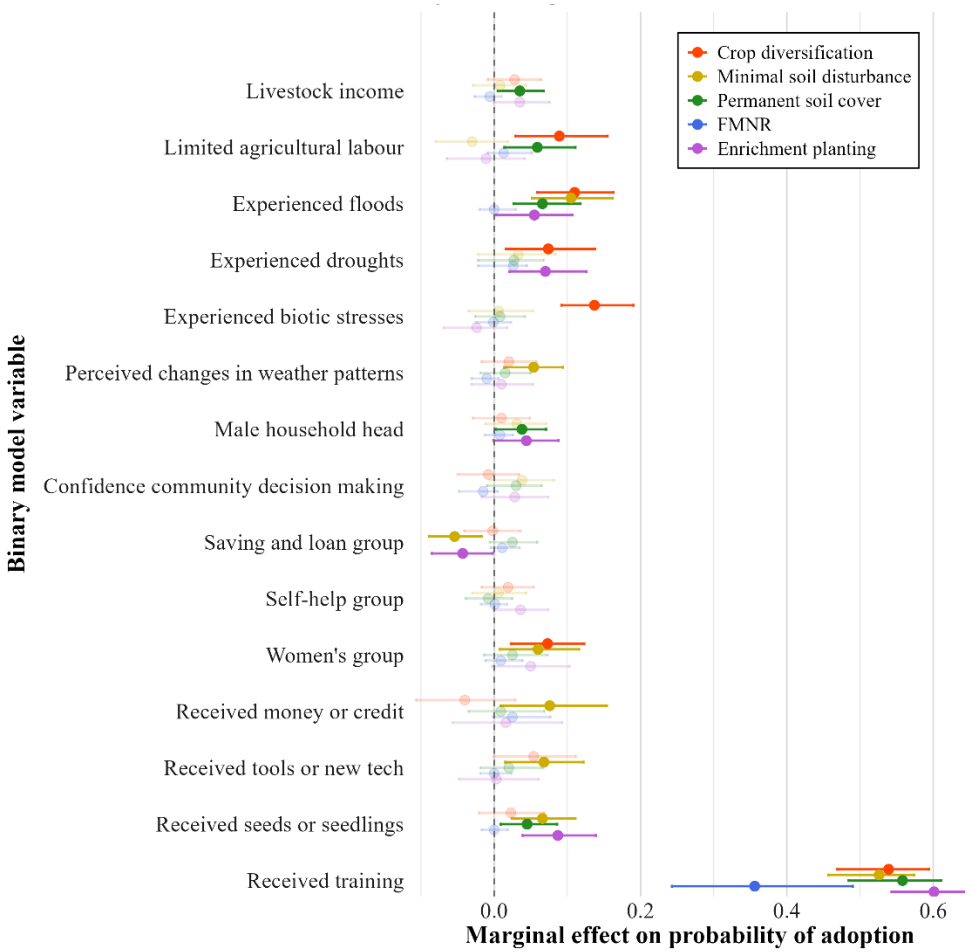


Figure 2-4. Average marginal effects (coloured points) and 95% confidence intervals (bars) of binary variables calculated from the results of five logistic regression models. Full opacity indicates significance ($p < 0.05$). Non-significant results are faded.

2.5 Discussion

Our results revealed several key findings. Higher food insecurity and lower incomes greatly reduced the probability of adopting FMNR and to a lesser extent crop diversification and permanent soil cover. Experiencing environmental stressors also had strong positive influences on adoption, particularly for crop diversification. Receiving training was clearly the dominant positive predictor of NbS adoption overall. Social variables like belonging to various self-help groups were generally some of the least relevant variables for predicting NbS adoption behaviours. Finally, The McFadden R^2 values ranged from 0.358 to 0.462 indicating good fit across all models (McFadden 1979).

2.5.1 Economics

High levels of food insecurity were associated with reduced adoption of NbS, specifically for permanent soil cover and FMNR. Adoption of these two practices requires sacrificing short-term biomass uses for long-term farm benefit. The behaviours observed in our study align with literature. Farmers experiencing immediate food insecurity are less likely to adopt practices that focus on generating long-term benefits (Nata et al. 2014). Food insecure farmers will sell available plant residue or use it as livestock feed, to get immediate utility from biomass (Giller et al. 2009); this therefore hinders adoption of FMNR. Farmers facing immediate food insecurity are forced to overexploit local natural resources, such as cutting down trees for immediate use rather than protecting them for future benefit (Kuyah et al. 2023). We cannot directly determine from our results if the relationship between lower food insecurity and higher adoption reflects already adopted practices reducing food insecurity or if permanent soil cover and FMNR are inherently less applicable to food-insecure farmers.

Annual household income had a strong influence on adoption. Higher incomes were positively associated with crop diversification and FMNR in our logistic regression models. Predicted probabilities rise sharply at low-income levels, but the marginal gains in adoption become progressively smaller as income increases. This reflects the diminishing proportional impact of a fixed KES 10,000 increase: for a household earning KES 10,000, an additional KES 10,000 represents a 100% increase in income, whereas for a household earning KES 100,000, the same increment represents only a 10% increase. Taken together, these results indicate that additional income has the greatest impact on adoption among the poorest households. For context the rural overall poverty line, which includes allocations for shelter, clothing and personal care, in Kenya is KES 4,358 per month per adult equivalent or KES 52,296 per year (KNBS 2024).

Higher incomes increasing adoption of new practices has been observed elsewhere (Sabastian et al. 2014; Foguesatto and Machado 2021; Nyang’au et al. 2021). This effect may be attributed to changes in farmers' risk preferences. Higher income may decrease risk aversion (i.e., willingness to try new crops or

new practices) and increase farmers' capacity to mobilize resources (Asravor 2018). Conversely, lower incomes may place households in a poverty trap, in which diminished risk tolerance limits their ability to adopt novel practices (Jumare et al. 2018). Crop diversification adds sources of risk that may not be palatable to low-income farmers. Crop diversification requires more planning, knowledge and management complexity (Giller et al. 2009; Thierfelder et al. 2016), as well as navigating uncertainties around marketability, particularly for legume crops (Giller et al. 2009). These factors may explain the lower adoption rates observed amongst low-income households. Additional supports may need to be provided alongside the promotion of crop diversification to ensure its accessibility to low-income farmers. FMNR is promoted as a "low-cost" practice (Wanjira et al. 2020; Rinaudo et al. 2021), but our results suggest that income can act as a barrier. Like with food insecurity short term needs may take priority over long term benefits.

Alternatively, the relationship between reduced adoption of NbS at low income and low food security may relate to incentives and available alternatives rather than practice/need misalignment. Farmers with small land holdings and low income from agriculture will have little incentive to innovate as large proportional gains in productivity will only produce small absolute gains due to low baseline productivity. This can result in cases where even if potential yield gaps are closed the farmer is still incapable of meeting their food and income needs (Giller et al., 2021). This may discourage farmers from attempting these practices especially in areas where land or water is restricted. Instead of innovating and adopting new practices such as FMNR, permanent soil cover and crop diversification , they may turn to wage labour to meet their food and income requirements (Giller et al., 2021).

Livestock income was associated with a higher probability of adopting permanent soil cover. This was unexpected, as one of the major constraints of permanent soil cover is competition for livestock feed (Giller et al. 2009; Valbuena et al. 2012; Thierfelder et al. 2015). This may indicate that in our study area competition for crop residues did not strongly influence adoption decisions. Livestock income was not associated with increased adoption of FMNR. Other authors have reported that one of the main reported

benefits of FMNR is to increase forage production for livestock (Kuyah et al. 2023). Because of this, previous studies have shown that the number of livestock owned increases the probability of adopting FMNR (Camara et al. 2023). We expected similar results in our study. Given data constraints, we used livestock income (measured as a binary variable), though we recognize that a numeric measure of livestock income or quantity of livestock may provide more predictive power.

Our results show that farmers who report limited agricultural labour availability had increased probabilities of adopting crop diversification and permanent soil cover. These findings contradict other studies where greater labour availability increased CA adoption, due to the extra labour helping to deal with mulching or planting cover crops (Ngwira et al. 2014). There are both criticisms and benefits of CA regarding labour. Proponents argue that CA saves labour through the reduced need for tillage, while its critics highlight the potential increase in weeding labour (Giller et al. 2009; Montt and Luu 2020). Mulching may also require a significant labour input if plant residues are being concentrated to a particular area (Bouwman et al. 2021). The positive relation between limited agricultural labour availability and adoption of these two CA components could be explained in two ways. Farmers may be adopting CA as a perceived solution to their labour constraints, or CA adoption itself may be the cause of the reported labour shortages. The latter explanation seems more likely based on empirical evidence (Montt and Luu 2020). Additionally, if CA were appreciably reducing labour demands, then farmers who adopted it should no longer be reporting challenges with limited labour.

2.5.2 Environmental Awareness

Exposure to flooding increased adoption of all NbS except FMNR. Other authors have shown that a perceived increased in floods increases the probability of adopting crop diversification and agroforestry (Tanti and Jena 2023). In contrast, using measures of actual flood exposure, the same study found no significant effects on practices comparable to those examined here. In Malawi, the probability of flood shocks did not affect adoption (McCarthy et al. 2021).

Drought exposure increased the adoption of crop diversification and enrichment tree planting. The literature shows that drought exposure can stimulate the adoption of other improved practices, such as drought-tolerant maize (Holden and Quiggin 2017) and minimal soil disturbance (Etumnu et al. 2023). Other studies have reported conflicting results. For example, one study from India found that experiencing drought decreased the probability of adopting crop diversification and agroforestry, yet the same study reported that perceiving droughts as becoming more common *increased* the probability of adopting crop diversification (Tanti and Jena 2023). Another study reported that farmers' perceptions of drought decreased adoption of no-till/minimum tillage, while drought exposure had no significant impact on crop diversification (Pilarova et al. 2018). McCarthy et al. (2021) observed that experiencing drought was not associated with increased adoption of any practices. There was little direct evidence in reviewed literature to support our findings that drought exposure specifically increases adoption of crop diversification and enrichment planting.

Experiencing biotic stresses significantly increased the predicted probability of adopting crop diversification. Biotic stressors such as crop pests and diseases, present considerable challenges for small holder farmers. Recently introduced pests such as fall armyworm have multiplied this challenge (Niassy et al. 2021). The strong effect of experiencing biotic stresses on crop diversification highlights the ability of this practice to increase the resilience of farming systems. But in other contexts, perception of pests was not a significant determinant of adoption of crop rotation (Pilarova et al. 2018).

The predicted probability of adopting minimal soil disturbance was higher among farmers who reported perceiving changes in weather patterns. Similar studies found that farmers are more likely to adopt sustainable agriculture practices, including green manures or legume crop rotations, if they perceived climate change and changing weather (Makate et al. 2017; Funk et al. 2020; Tanti and Jena 2023). Furthermore, farmers are able to identify these climatic changes, as demonstrated by correlations between farmer perceptions and long term weather station data (Nyang'au et al. 2021). To some degree these results suggest that farmers, even in areas with potentially low access to information and low

adaptive capacity, are effectively self-assessing their changing environment and implementing NbS in response.

One of the significant findings of this paper is that environmental stressors—namely experiencing droughts, floods, and biotic stresses—were associated with increased adoption of NbS. Broady, we reason that farmers experiencing these challenges are seeking solutions to mitigate future exposure and are identifying NbS as a part of that solution. There is evidence supporting the ability of NbS to increase farm and landscape resiliency to environmental stresses. CA, using intercrops, can increase yield stability (Madembo et al. 2020), increase yields through increased land equivalency ratios, and suppress pests (Loewen et al. 2025). In Malawi, yield reduction, from floods and droughts was mitigated through the adoption of legume intercrops and through tree planting in the form of greenbelts (McCarthy et al. 2021). CA also has been shown to increase water infiltration and reduced erosion (A.M. Abdallah et al. 2021). For FMNR and enrichment planting there are similar positive effects which can help increase farm and landscape resiliency. These benefits include food provisioning and increasing dietary diversity (Binam et al. 2015), increased soil carbon, which helps protect the long term productivity of the land (Kuyah et al. 2023) reduced erosion (Kurowska et al. 2022), and providing the means to stockpile resources such as fodder and wood for difficult years (Brown et al. 2011).

The influence of environmental stressors on motivating NbS adoption was particularly strong for crop diversification. These results indicate that farmers are choosing crop diversification as a key strategy to respond to these stresses. Crop diversification offers nearly full benefit to the farmer within one growing season. Diversified diets and income (if the new crop types are sold) are available at harvest offering insurance if one crop fails due to environmental challenges. This is in contrast to the other NbS examined in this study where benefits may take years to accrue (A.M. Abdallah et al. 2021).

While our results show that farmers exposed to environmental stresses are more likely to adopt NbS, we also show that farmers with lower income and food security have reduced probabilities of

adopting these practices. Additionally, environmental stresses can negatively impact food security (McCarthy et al. 2021) and income (Wineman et al. 2017). Combining these points raises an important question: what is the net effect of environmental stress exposure, given that it may simultaneously increase adoption and indirectly reduce adoption by creating poverty and hunger? Our model is unable to answer this question. We did not quantify the extent to which environmental exposure reduces income or increases food insecurity. Therefore, we cannot determine the net effect of higher exposure driving adoption versus the reduction in adoption due to lower incomes and food insecurity caused by higher environmental stresses. This is an important topic of future research.

These findings have several implications. First, they indicate that farmers are responding with positive coping strategies to environmental stressors. Second, since farmers are already adopting NbS in response to stressors, adoption might be strengthened further by educating farmers on the predicted increases in environmental stressors under climate change (IPCC 2023b).

2.5.3 Social Context

Our results showed that male headed households were more likely to adopt permanent soil cover and enrichment planting. This result is inline with literature. Most studies have found that male headed households were more likely to adopt improved practices, including components of CA and enrichment tree planting (Deressa et al. 2009; Mazvimavi and Twomlow 2009; Funk et al. 2020; Foguesatto and Machado 2021; Oduniyi et al. 2022). Others found that both female and male-headed households had increased adoption depending on the intervention (Hangamu et al. 2024). The effect of gender also appears to vary by country (Twyman et al. 2014).

Based on the anecdotal perceptions from implementing partners, women are eager to adopt these practices. However, the partners also noted that women face substantial cultural barriers that limit their decision-making power, access to information, access to land, labour and access to resources. The reduced probability of NbS adoption among female-headed households in our study is likely explained by these

challenges. Other authors have identified similar barriers limiting women's uptake of agricultural practices. These challenges include gender and cultural barriers that exclude women from decision-making, lower education levels among women, reduce access to training, challenge accessing credit, and restrict land ownership, and agricultural extension that favours men (Boudalia et al. 2024). As a result, women may be less aware of NbS (Twyman et al. 2014). The same study, which included a location in Makueni County, noted that when women were aware of a NbS, they had similar, and in some cases higher, adoption rates than men (Twyman et al. 2014). Our results add to the existing body of literature that identifies the need for further efforts to empower women, dismantle cultural barriers, and facilitate the equitable adoption of NbS.

Variables such as participation in community decisions, savings and loan groups, self-help groups, and women's livelihood groups all contribute to social capital, which considers relationships between people as an asset (Pretty and Ward 2001). Social capital offers observable benefits such as support networks and trust (Pretty and Ward 2001). As a result, we expected that variables related to social capital would have consistent positive effects. However, women's livelihood groups were the only social capital variable we measured with a significant positive effect in this study.

In other studies, social capital generally has positive effects on adoption, although the specific variables used vary. Deressa and colleagues (2009) found that higher farmer-to-farmer extension and greater numbers of relatives in a local area increased the adoption of soil conservation and tree planting. Hangamu et al. (2024) found that participation in village meetings increased the probability of adopting soil conservation as a drought adaptation strategy. Similarly, other authors have observed that the adoption of CA was predicted by the involvement in farmer cooperatives and community groups (Ngwira et al. 2014; Oduniyi et al. 2022). In Ethiopia, research demonstrated the importance of social capital in supporting the adoption of crop rotations and conservation tillage (Teklewold et al. 2013). An early review of CA studies cautiously suggested social capital may be a universally positive variable (Knowler and Bradshaw 2007). Conversely, others have observed that community organization membership did not

affect FMNR adoption. (Ndegwa et al. 2017). In this case authors suggest that this result may be due to a lack of community groups specifically pertaining to agriculture and environmental protection. Women's livelihood groups increased the adoption of both crop diversification and minimal soil disturbance. The significant effect of this group type in contrast to the insignificant or negative impact of the other social capital variables requires further study.

We also observed that participation in savings and loan groups was associated with reduced predicted probabilities of adopting minimal soil disturbance, and enrichment planting. Savings and loan groups may prioritize short-term investments with reliable income generation and quick returns, in contrast to the long-term benefits associated with enrichment planting. These groups are often used to help meet emergency cash needs, bridge seasonal food insecurity, or investment in immediate farm needs (Brunie et al. 2017). Additionally, tree planting faces challenges in arid environments, such as low or variable survivability (Rinaudo et al. 2021; Eshete et al. 2023), which adds uncertainty to the profitability of such enterprises. Farmers who face difficulties in accessing traditional forms of credit may be simultaneously driven away from minimal soil disturbance adoption due to limited access to inputs or equipment requirements (Corbeels et al. 2015) and towards savings and loan groups as an alternative means to access credit (Waaswa et al. 2024). Difficulties accessing credit has, in multiple contexts, been shown to be a barrier to adoption of NbS and other improved agricultural practices (Deressa et al. 2011 Feb; Teklewold et al. 2013; Hangamu et al. 2024).

The inconsistent effects of social capital observed in our study run counter to the suggestion by Knowler and Bradshaw, (2007) that social capital may serve as a universal predictor of adoption. Social capital may benefit communities broadly, but based on our results, these benefits may not always translate directly into increased adoption of specific agricultural practices. Our dataset was collected prior to Nature+ project activities beginning. Therefore, existing local community groups are unlikely to have been focused on NbS adoption. The effectiveness of community groups and social capital may be very different once project activities began and active support for NbS adoption was provided to these groups.

2.5.4 Support

In our study, receiving training was the most important predictor of increased adoption of NbS. In addition, we included three forms of receiving tangible support: money or credit, tools or new technology, seeds or seedlings. Those receiving these forms of support also support adoption. Our findings are consistent with literature. Multiple authors have shown that access to credit supports the adoption of NbS practices (Deressa et al. 2011 Feb; Hangamu et al. 2024), while a lack of credit reduces adoption (Deressa et al. 2011 Feb; Teklewold et al. 2013; Hangamu et al. 2024). Input subsidies have been shown to improve adoption of crop diversification and minimum soil disturbance (El Bakali et al. 2023) and access to seeds and fertilizer can increase the intensity of conservation agriculture adoption (Mazvimavi and Twomlow 2009).

The most influential determinant of adoption of the selected NbS was whether the farmers received training (including information) on a particular NbS. The change in predicted probabilities for this variable ranged from 35.6% to 60.1%. These results highlight that lack of farmer knowledge is a key barrier to adoption of all five studied NbS. Other authors have similarly identified limited access to information as a major barrier preventing the update of comparable NbS (Ngwira et al. 2014; Sabastian et al. 2014; Hangamu et al. 2024). Our results demonstrate the effectiveness and potential impact of extension that could provide information or training of these NbS to farmers. To illustrate this, only four percent of surveyed households reported receiving training on FMNR. Based on our model, if no farmers had received such training the probability of adoption would be 1.4%. However, if all farmers had received training the adoption would be 37%. Widespread extension could make FMNR widely adopted.

2.5.5 Survey Limitations and Recommendations

This study used an existing, previously unanalyzed data set. As a result, the objectives were shaped around the potential of the available data rather than defined objectives guiding the design and development of the survey. This restricted what variables could be included. As a result, several key variables commonly included in adoption studies (Knowler and Bradshaw 2007b) were omitted, either

because they contained unreliable data or were not collected at all. Variables such as age, education level, land size, or asset ownership, have been shown to be important predictors of adoption (Knowler and Bradshaw 2007b) but were not included. While unavoidable in this study, the exclusion of relevant variables has the potential to obfuscate the true regression coefficients, effect size, and significance values (Antonakis et al. 2010).

Our income variable was limited in several ways. Income was based on annual household averages reported by survey participants. In many cases the participants taking the survey were not the head of their household. This may limit accurate estimation of income. Some authors have questioned the accuracy of self-reported income measurements, especially in developing countries or subsistence contexts (Deaton 1997). Farmers may or may not deduct input or wage expenditures when reporting income. This challenge is compounded with issues of recall bias and variability arising from season-to-season differences in growing conditions (Deaton 1997). These limitations imply some possible error in the income data, which could influence our results in unknown ways.

In our model, adoption was measured as a binary variable. Furthermore, adoption was self-reported by the farmer rather than defined using a discrete adoption threshold (i.e. defining permanent soil cover as average soil cover > 30%). In development contexts, such as the Nature+ project, farmers are often encouraged to attempt the interventions on a small portion of their land, allowing them to observe the benefits for themselves before further committing to the practice. Partial adoption of CA practices is evidenced in literature (Montt and Luu 2020). Farmers may run into constraints such as mulch availability when attempting to implement the practice on large areas (Bouwman et al. 2021).

A farmer who reported adopting a practice may have only adopted the practice on 10% of their land. They would be indistinguishable from a second farmer, who adopted the same practice on 100% of their land. In the first case only a fraction of the potential ecological, social, and economic benefits are realized. Distinguishing these two groups may reveal valuable insights on differences between them.

Additionally establishing a discrete adoption threshold (e.g. permanent soil cover equals > 30% ground cover) would improve interpretability.

Despite the strong influence receiving of training on NbS adoption, the vagueness what these training interactions or exchanges of information entailed is a limitation in our study. A brief explanation of a practice versus a detailed farmer workshop, will likely result in different adoption outcomes, yet our dataset does not distinguish these differences. One potential source of information likely included onboarding processes for the program. It is also unclear whether "receiving information and training" extended to informal communication amongst farmers. As a result, there may have been inconsistencies in how informal communication was interpreted or recorded by enumerators.

Our model does not directly determine the causality between independent variables and the NbS (dependent variables) as is common amongst similar studies (Antonakis et al. 2010). For some variables in particular there is strong evidence to suggest some form of reverse causality. For example, adoption of CA and FMNR can increase the incomes of farmers (Haglund et al. 2011; Oduniyi et al. 2022). Therefore, the observed association between higher-income farmers and crop diversification or FMNR may be partially explained by the practices themselves contributing to higher income. We also found that food insecurity reduced the adoption of permanent soil cover and FMNR. However, adoption of these NbS is also expected to increase food security (Fentahun and Hager 2010; A.-H. Abdallah et al. 2021). Again, our model cannot distinguish between the impact of adopting an NbS on food security and the impact of food (in)security on farmers' decisions to adopt NbS. The issue of causality could be addressed using different study designs. Panel data, as used by several authors (McCarthy et al. 2021; Spurk et al. 2025) would enable tracking changes over time with in the same individual. Other options to address causality include utilizing regression discontinuity, difference-in-differences, and instrumental variables (Antonakis et al. 2010; Wuepper and Finger 2023).

Our study considered the adoption of NbS practices in isolation. In reality, adoption of one NbS may influence the likelihood of adopting additional practices (Teklewold et al. 2013). Some practices may be complementary, while others may function as substitutes. Further investigation is warranted to understand how CA and FMNR practices interact in terms of adoption.

2.6 Conclusion

This paper contributes to the existing understanding of variables that act as promoters and barriers to CA (crop diversification, minimal soil disturbance, and permanent soil cover), FMNR and, enrichment planting adoption in Kitui and Makueni County, Kenya. Results obtained from logistic regression models showed several variables with notable impacts on the predicted probability of adopting NbS. Higher household income was associated with increased adoption, whereas greater food insecurity was associated with decreased adoption.

Both low income and food insecurity decreased the probability of adopting FMNR. While lower income decreased the probability of adopting crop diversification, and food insecurity decreased the probability of adopting permanent soil cover. This suggests that these practices may have lower applicability to poor and food insecure farmers or these practices may need to be pared with other supports to be successful. Exposure to environmental stressors, including drought, floods, biotic stressors (crop pests and diseases), as well as awareness of changing weather patterns, also increased the likelihood of adopting NbS. These results identify that farmers are choosing NbS as a positive coping strategy. We predict that educating farmers on how climate change is expected to worsen these environmental stressors may be a means by which to boost adoption. Male headed households had higher probabilities of adopting, indicating systemic barriers facing women headed households. Providing tangible supports for adoption, which included money or credit, tools or new technology, and seeds or seedlings, increased adoption emphasizing the ability of incentives to help overcome adoption barriers. Besides women's livelihood groups no other social capital variables were associated with increased adoption, which included involvement in community decision making, self-help groups and savings and loan groups.

Participation in savings and loan groups were shown to decrease adoption of minimal soil disturbance and enrichment planting. We suggest that the low impacts of social capital may be due to no coordinated efforts to engage the studied groups in facilitating information and adoption of NbS. Receiving training was the dominant predictor of whether a farmer would adopt a practice. Given the low rates of current training availability in these communities, we identified and quantified substantial potential to increase adoption through expanded access to information and training opportunities. These findings help identify the enabling environment required for successful NbS uptake and highlight which aspects of that environment need to be co-promoted by development projects for successful outcomes.

CHAPTER 3. THE IMPACT OF FARMER MANAGED NATURAL REGENERATION ON INSECT BIODIVERSITY, SOIL HEALTH, GROUND COVER AND BIOMASS

3.1 Abstract

Farmer-managed natural regeneration (FMNR) is an accessible land management practice that has been widely promoted in the Sahel region of Africa. It provides benefits to both landscapes and farmers, including restored tree cover, increased productivity, and new income sources. Together, these outcomes contribute to the development of more resilient agroecosystems. However, despite growing attention and uptake, a large portion of the evidence base for FMNR relies on farmer perceptions and reports from development projects where the focus is on impacts to livelihoods rather than measured biophysical responses. There is a need to complement these forms of knowledge with quantitative in-field biophysical measurements to develop a more complete understanding of the impacts of FMNR on ecosystem services.

This study seeks to address this research gap by quantifying the impacts of FMNR on soil health, ground cover, biomass, and insect diversity. Across 25 farms, FMNR increased soil respiration and, as rated by farmers, improved soil structure and water infiltration. We also found a significant positive relationship between the farmer-focused hoe test and soil respiration, indicating that farmer perceptions and scientific observations were aligned. Across 21 of the 25 farms, effective insect diversity at the order level was significantly higher in FMNR pitfall traps compared to the business-as-usual control treatment. Finally, based on a subset of four farms, these results provide preliminary evidence of improved ground cover, higher herbaceous biomass and evidence of farmers using stockpiled resources in FMNR plots during periods of drought. Together, these results quantify the potential of FMNR to strengthen agroecosystem resilience through improvements in soil health, biodiversity and productivity.

3.2 Introduction

Agriculture and humanity face a dual crisis of climate change and biodiversity loss (Cowie et al. 2022; IPCC 2023b). These challenges have adversely impacted and will continue to impact agriculture.

Heat and moisture extremes associated with climate change result in yield losses (Lesk et al. 2022) and extreme weather events are expected to become more frequent (IPCC 2023b). At the same time, agricultural continues to contribute to biodiversity loss (Wagner 2020) and greenhouse gas emissions (IPCC 2023b).

Coupled with these global challenges, many landscapes across East Africa have experienced a combination of deforestation, overgrazing and erosion. Such forms of landscape degradation have been widely observed in Kenya (Lohbeck et al. 2018). This degradation is partially due to population growth which has greatly increased demands for food, firewood, tree products, fodder, and browse for grazing (County Government of Kitui 2018). In a reinforcing cycle, environmental degradation is further decreasing the ability of agroecosystems to sustain people (Mugwe et al. 2009).

Smallholder farmers in East Africa face these challenges with limited resources and adaptive capacity (Walpole et al. 2013). Therefore, it is critical to develop and promote agricultural systems that can simultaneously meet the needs of people and the environment while increasing the resilience of these systems to future climate and socioeconomic shocks. Sustainable agricultural development is recognized as a crucial component in achieving positive ecological, socioeconomic outcomes (Perfecto & Vandermeer, 2010), and thus addressing the challenges faced by farmers. The Nature+ program led by the Canadian Food Grains Bank seeks to help address these challenges by implementing various nature-based solutions (NbS). NbS are defined as “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al. 2016).

Farmer-managed natural regeneration (FMNR) is one approach being used in Kenya to strengthen agroecosystems. As the name suggests, FMNR is a farmer-directed approach to the regeneration of plants on agricultural land. While its precise implementation is flexible and adapted to the needs of farmers, in general, it relies on the living root systems of cut-down trees and on soil seed banks, which are often still

present on overgrazed and deforested landscapes. The process of implementing FMNR begins with farmers identifying a degraded piece of land on which they wish to implement the practice. Farmers strategically manage existing woody vegetation by pruning the multi-stemmed regenerating trees into one to three main stems and removing lower branches to encourage vertical growth. Many of the trees that attempt to regenerate would otherwise take on a small bushy appearance because of repeated browsing by livestock and removal by farmers (Rinaudo et al. 2021). Additionally, some farmers may clear areas overgrown with thorny shrubs to open areas for future grazing or fodder production (Wanjira et al. 2020; Rinaudo et al. 2021).

A secondary component of FMNR involves managing livestock access particularly cattle and goats, which are the dominant livestock species in the project area. Since many tree and shrub species in these arid environments contain thorns, branches from pruned trees and cleared shrubs are used to create barriers around FMNR sites. This stops uncontrolled grazing and protects regenerating plants from being immediately grazed. Farmers may still allow livestock to graze intermittently especially during periods of droughts (Wanjira et al. 2020). FMNR management practices change over time transitioning from a regeneration phase where trees are pruned and regeneration is actively promoted, to a maintenance phase during which grazing is controlled, wood products are harvested, and tree densities are kept stable (Rinaudo et al. 2021).

FMNR can be implemented across a range of agricultural systems. Some FMNR projects promote the practice to create an agroforestry system. Tree species such as *Faidherbia albida,* which shed their leaves during the cropping season, are often used to minimize competition with crops while contributing nitrogen to the soil (Reij and Garrity 2016). In other pastoral based communities, including parts of East Africa, FMNR is promoted to improve fodder production and restore forests (Weston et al. 2015; Rinaudo et al. 2021). In the present study, the emphasis is on fodder and forestry products rather than agroforestry for cereal and legume production. Additional practices that may be utilized alongside FMNR include

enrichment planting of trees, seeding of grasses, and soil and water conservation practices, such as terraces and bunds. Collectively these additional practices are termed FMNR+.

FMNR has economic advantages as it is a more cost-effective approach to landscape regeneration compared to tree planting. Furthermore, smallholder farmers are likely to already own the tools needed for implementation (Wanjira et al. 2020). FMNR can also be implemented in a variety of ways to meet the unique contexts and needs of individual farms (Rinaudo et al. 2021). Some projects have promoted and implemented adoption of FMNR at a cost of less than 20 USD ha^{-1} (Reij and Garrity 2016). In contrast, tree planting campaigns can exceed 400 USD ha^{-1} (Rinaudo et al. 2021). Tree planting also faces additional challenges, including low tree survival rates, the necessity for complex and burdensome organizational structures, the acquisition and transport of saplings, ongoing tree protection and management requirements, and cultural concerns of restricting land access to pastoralist groups (Yiridomoh et al. 2024; Zhu et al. 2025).

Many of the currently quantified outcomes of FMNR focus on benefits to people. FMNR can increase income (Haglund et al. 2011; Binam et al. 2015; Weston et al. 2015) and food security (Binam et al. 2015; Binam et al. 2017; Mensah et al. 2024). Social benefits, such as increased community leadership capacity, have also been proposed (Weston et al. 2015). Additionally, FMNR can increase wood and non-wood forest products (Kuyah et al. 2023) and honey production (Mensah et al. 2024). Rinaudo et al., (2021) provides an extensive list of additional proposed and reported benefits including wild foods, gums, resins, and traditional medicines.

Biodiversity in ecosystems enhances resilience (Oliver et al. 2015). High levels of biodiversity fill a wide range of ecological niches within an ecosystem resulting in higher primary productivity (Oehri et al. 2017; Chen et al. 2018), which can produce secondary benefits such as increased soil organic carbon (Lohbeck et al. 2018; Janzen et al. 2022). Biodiversity effects in natural areas can also spill over into surrounding croplands (Vogel, Poveda, et al. 2023).

Most research on the benefits of FMNR on biodiversity are restricted to plant diversity. One study in Kenya noted a positive trend in plant species abundances over four years following FMNR establishment (Choge et al. 2024). Studies elsewhere in Africa have observed that FMNR increased tree diversity (Haglund et al. 2011; Larwanou and Saadou 2011; Weston et al. 2015). In an assisted natural regeneration system, a practice similar to FMNR, tree richness as well as Shannon and Simpson diversity increased following 6-18 years of grazing exclusion (Marcacci et al. 2025). However, there is limited mechanistic understanding of how this diversity enhances agroecosystem functioning (Larwanou and Saadou 2011) as well as how land use influences biological communities in smallholder contexts (Walpole et al. 2013).

Understanding the effects of FMNR on insect biodiversity is important because insect diversity can serve as an indicator of broader diversity and environmental integrity (Landmann et al. 2023). These authors noted that stingless bees (Meliponini), dragonflies (Anisoptera), and butterflies (Papilionoidea) can be an important indicator taxon in certain African landscapes. Insect biodiversity, in some cases, can also act as an early warning sign for ecosystem change (Roque et al. 2018).

Broader ecological literature can provide insight into of the response of insect biodiversity to FMNR. For example, a Kenyan study reported increases in insect biodiversity in response to former cropland regenerating back to forest (Banks et al. 2022). They noted regenerated forest had insect biodiversity comparable to the surrounding undisturbed forest. Furthermore, human managed ecosystems can also boost biodiversity when if resources are managed responsibly and human activities create new types of habitat (Bugalho et al. 2011). Broadly speaking, naturalized areas can increase richness and diversity of plants, vertebrates, and invertebrates (Gonthier et al. 2014). These diverse and functional ecosystems can self-regulate with natural enemies controlling pest outbreaks (Yadav et al. 2023).

FMNR can increase soil health through various mechanisms. Trees can concentrate nutrients and soil carbon around their crowns (Bayala et al. 2020), while leguminous trees such as acacia species and

the commonly used *Faidherbia albida,* contribute nitrogen to the soil. Consistent with these mechanisms, parkland agroforestry systems had 32% higher nitrogen concentration on average compared to a treeless control (Bayala et al., 2018). Grasses growing within FMNR systems have the potential to impart large benefits. In various natural systems consisting of trees growing amongst grasses, most soil organic matter is derived from grasses (Wigley et al. 2020; Zhou et al. 2023). Consequently, promoting grass growth represents and important objective of FMNR and of the present study.

While there is limited existing empirical evidence of FMNR systems on the impact of soil health, farmer perceptions documented in multiple studies do suggest a strong relationship between FMNR and a variety of soil health benefits. Farmers in Ghana, reported that FMNR helped support soil formation, control soil losses from soil erosions, and improve soil fertility (Yiridomoh et al. 2024). In Senegal, farmers most frequently identified improved soil fertility as a benefit of FMNR, while soil moisture conservation was the third most frequently reported benefit (Camara et al. 2023). In Ethiopia (Kibru et al. 2021), farmers reported increased soil fertility and subsequently higher fodder and fruit availability from FMNR. Additionally, the previously discussed improvements in crop yields and food security (Binam et al. 2015; Weston et al. 2015) may be partially attributable to soil improvements increasing resource partitioning.

Most reports of soil improvements and the impacts of FMNR are based on farmer perceptions (Camara et al. 2023; Yiridomoh et al. 2024). Additionally given that many FMNR projects are promoted by development agencies, there is a large focus on benefits to people rather than the environment (Kandel et al. 2021; Bonye 2024; Nyanhanda et al. 2024). As a result, empirical evidence quantifying biophysical mechanisms, such as changes in ground cover, soil function, and biodiversity, remains scarce in Kenya and East Africa (Chomba et al. 2020). The objective of this study, therefore, is to establish a preliminary understanding of how FMNR influences four interconnected biophysical parameters: soil health, ground cover, herbaceous biomass, and insect diversity. We hypothesize that FMNR, through increased ground cover and biomass inputs, will improve the observed soil health parameters compared to the business as

usual (BAU) practices used by farmers. Additionally, we hypothesize that that FMNR will facilitate higher insect biodiversity.

3.3 Methods

3.3.1 Site Selection and Characterization

Study sites were mostly located within Kitui County Kenya, and two farms were within the neighbouring Makueni County (Figure 3-1). In Kitui County, 87% income in the rural population is earned from agriculture. The food poverty rate is 39%, above the national average of 32% (County Government of Kitui 2018). The topography consists of a mix of relatively flat lands and rolling hills to the east and northeast as well as the Yatta plateau. Altitudes range from 400 m to 1800 m across the county. About 25% of land holders have title deeds and the average farm size is 4.4 ha. The total population density across the county is 37 persons per km^2 (County Government of Kitui 2018). Soil texture was qualitatively assessed on each farm. While there was some variability on the assessed texture, most commonly the soil was identified as sandy loam, clay loam, and sandy clay loam (Table B-3). Daily high and low temperatures (30-year average from 1991-2020) on studied farms are 30.1 °C and 16.8 °C (Abatzoglou et al. 2018).

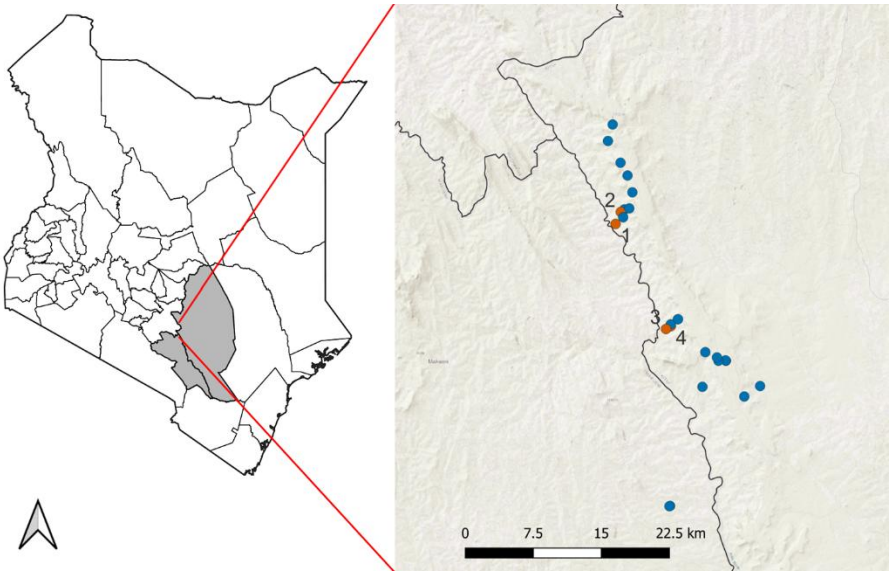


Figure 3-1. Locations the of the 25 sampled farms within Kenya. The four labeled orange markers belong to the detailed focal farm dataset, and the 21 blue markers represent the remaining farms in the insect and soil dataset.

Most areas of Kitui County are semi-arid. Thirty-year (1991-2020) average rain fall, as measured across four farms in the study area was 646 mm $year^{-1}$ (SD = 206) (Funk et al. 2015). Rainfall in this region occurs in a bimodal pattern resulting in two growing seasons; these are termed ‘the long rains’, which occurs March to May, and the ‘the short rains’ which occurs October to December (Figure 3-2), but the rain fall is often erratic and unreliable. In 2024, precipitation was well above average, with 1018 mm accumulating, and 919 mm accumulating in 2025 (Funk et al. 2015).

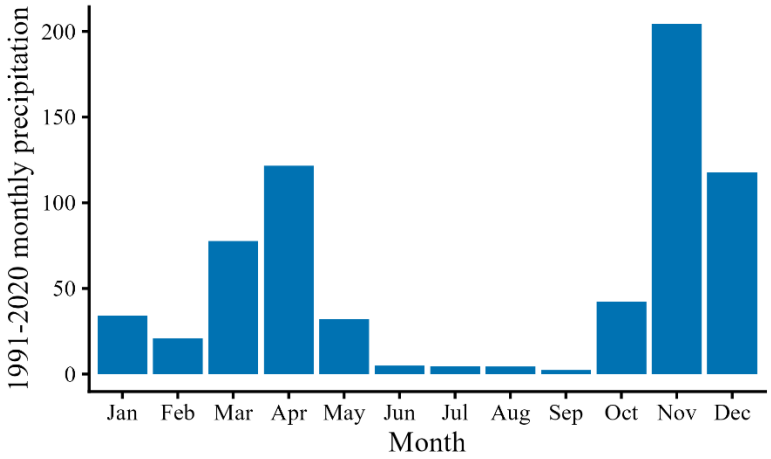


Figure 3-2. Monthly 30-year precipitation normals (1991-2020), averaged across four farms.

In the long rains of 2024, the growing season leading up to sampling, rainfall was 253% compared to the 30-year normal. During the short rains of 2024 (1st season of sampling), rainfall was 95% compared to the 30-year normal. During the long rains of 2025, rainfall was 210% compared to the 30-year normal. In the short rains of 2025, rainfall was 102% compared to the 30-year normal. Notably, in this final season the rains came late. Rainfall in the month of November was far below normal (

Figure **3-3**).

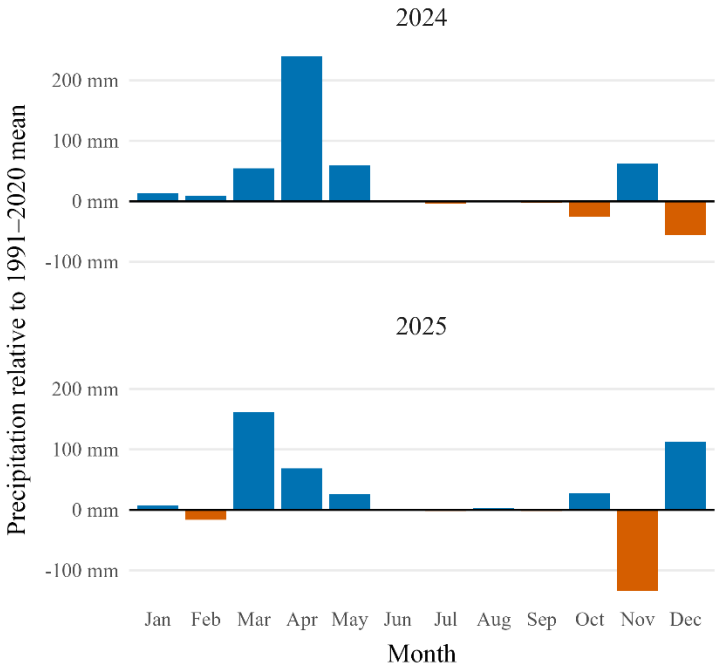


Figure 3-3. Monthly precipitation for 2024 and 2025 averaged across four farms compared to 30-year normals (1991-2020). Bars below the 0 line represent observed rainfalls below thirty-year averages.

3.3.2 Farm Characterization

Each farm included in the study contained a BAU treatment plot and a FMNR Information was collected on the FMNR and FMNR+ practices implemented by each farmer. On all 25 business as usual (BAU) plots farmers indicated grazing as an ongoing practice, some also indicated the existence of footpaths through their fields, these were used by the local community. Not all famers engaged in pruning in the FMNR plots. Additional practices recorded in the FMNR plots included fencing, enrichment planting of *Senna siamea* and *Azadirachta indica*, planting of the grass *Eragrostis superba,* water conservation structures, staking trees, and one farmer reported beekeeping (Table 3-1). Examples of several of these interventions are shown on Figure 3-4.

Table 3-1. Practices reported by farmers on 25 farms with paired BAU and FMNR treatments. Each farm may adopt multiple practices (e.g. pruning and fencing).

Treatment	Practices	Number of farms using practice	Percent of farms reporting the practice (out of 25)
BAU	Grazing	25	100
BAU	Footpath	7	28
FMNR	Fencing	22	88
FMNR	Pruning	19	76
FMNR	Enrichment planting	9	36
FMNR	Water conservation structures	8	32
FMNR	Grass planting	5	20
FMNR	Staking	4	16
FMNR	Beekeeping	1	4

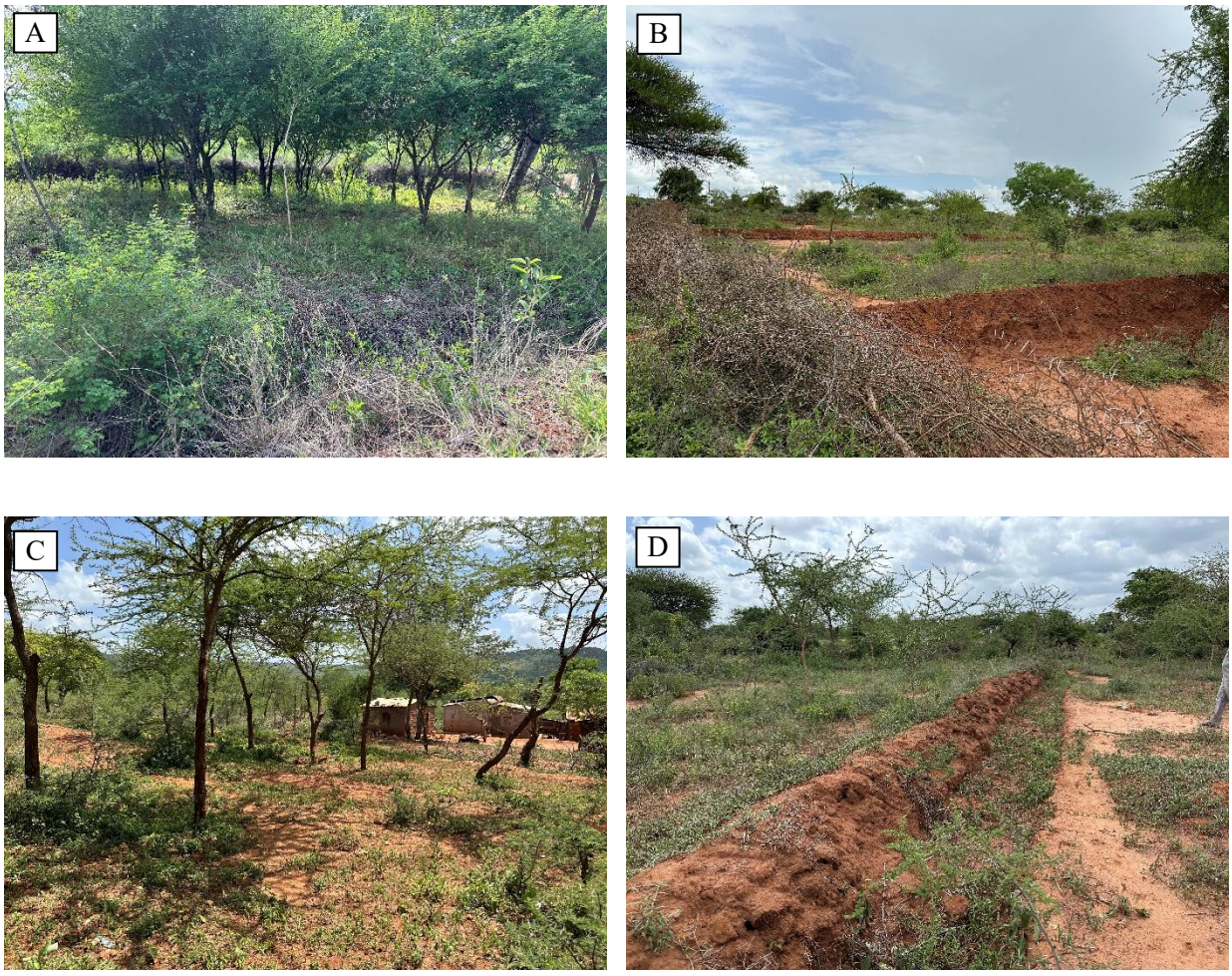


Figure 3-4. Examples of interventions being practiced on FMNR plots. (A) Pruned trees with grasses and herbaceous vegetation growing between them. This FMNR site was not included in data collection and was established over 5 years ago. (B) Natural fencing to restrict grazing in the foreground and soil bunds behind. (C) Trees with lower branches pruned away. (D) A soil bund with attempted grass planting in the depression.

3.3.3 Sampling

FMNR treatments were applied on 25 farms in Kenya. On each farm, a business-as-usual (BAU) treatment was also included in addition to the FMNR treatment. The FMNR treatment sites within a farm were selected by the individual farmers. Treatments were implemented between June 2024 and November 2024.

Three sampling protocols were followed resulting in three datasets referred to below as A) soil dataset, B) insect dataset, and C) focal farm dataset. The soil dataset contains soil health parameters taken

from all 25 farms included in the study. The insect dataset includes 21 of these 25 farms and includes insect data to the order level. The focal farms dataset includes four of the 25 farms and incorporates ground cover, biomass, insect data to the family level, and detailed baseline soil samples (Table 3-2)**.**

Table 3-2. Overview of the number of farms sampled and measurements taken.

Dataset name	Number of farms	Soil parameters	Baseline soil samples	Ground cover / biomass	Insect samples
Soil dataset	25	✓			
Insect dataset	21*				✓ Order level
Focal farm dataset	4*		✓	✓	✓ Family level

** The four farms used for detailed measurements and the 21 farms from the insect dataset are both subsets of the 25 farms in the soil dataset.*

3.3.3.1 Soil dataset

On 25 farms, Solvita soil respiration tests, slake tests for aggregate stability, hoe test, and water infiltration scores were taken. These metrics included both famer-focused, semi-qualitative measures (i.e., hoe test and water infiltration score) and empirical tests (i.e., Solvita test for soil respiration, slakes test for aggregate stability). Samples were taken twice. The first sampling period occurred between April 25, 2025, and May 30, 2025. The second sampling period occurred between December 16 and December 19, 2025.

For the hoe test, farmers strike the soil with a hoe until the depth of the hole reaches the hoe blade, this is repeated randomly 10 times across the plot. Based on the soil characteristics noted by the farmer as they strike the soil, they assign a score of 1–5 (Entz et al. 2022); (Table B-1). Water infiltration score is evaluated by asking the farmer to rate how quickly water is absorbed into the soil. This observation is repeated once for each plot and again is rated on a scale of 1–5 (Entz et al., 2022; Table B-1). The descriptions of the 1–5 rating scale for both the hoe test and water infiltration score were obtained

from Entz et al. (2022). These participatory methods have previously been successfully used in Kenyan smallholder contexts (Entz et al. 2022).

To assess soil respiration, Solvita basic field CO_2 tests (https://solvita.com/fieldtest/) were used to measure CO_2 production, which serves as a measurement for microbial activity in the soil. Soil samples from the top 15 cm were taken from four locations across each plot. Samples were aggregated by plot then one Solvita test was performed on the aggregate sample. The specific procedure used followed the instructions provided from Solvita. Briefly, a measured quantity of field moist soil is collected and placed in an airtight jar included in the test kit. A CO_2 sensitive gel paddle is placed along with the soil in the jar. The sealed jar is left to sit for 24 hours and left to incubate then the paddle colour is assessed using a reference sheet or a digital reader and is assigned a score of 0-5 based on colour. Four paddles were scored using a digital colour reader produced by Solvita, but due to battery issues the remaining samples were scored by comparing the paddle colours to printed chart included with the test kit. A higher value equates to higher CO_2 production and microbial respiration. Solvita respiration results were compared with results of the hoe test using correlation analysis.

Soil aggregate stability was assessed using the slake test. Intact soil aggregates, 4–8 mm in diameter, were collected from the topsoil and air-dried for 24 hours prior to testing. Aggregate stability was then visually scored using the *Slakes* mobile application developed by the Soil Health Institute (Fajardo et al. 2016). Following the instructions within the Slakes app, the soil aggregates were placed in a Petri dish of water and the dispersion of the peds was captured by a phone positioned above the Petri dish. A score of ~0.1 to 1 is given to each sample based on the ratio of the area occupied by the soil at the beginning and the end of the test. A higher value indicates higher aggregate stability.

3.3.3.2 Insect Dataset

Insects were sampled using both bee bowls and pitfall traps (Smelko 2026). Together this enabled capturing both flying and crawling insects. Samples were collected between April 25, 2025, and May 30,

2025. Three pitfall traps and four bee bowl stations were set up in each plot in random locations avoiding field borders (Figure 3-5). Given the variation in plot size exact distances to the field edges also varied.

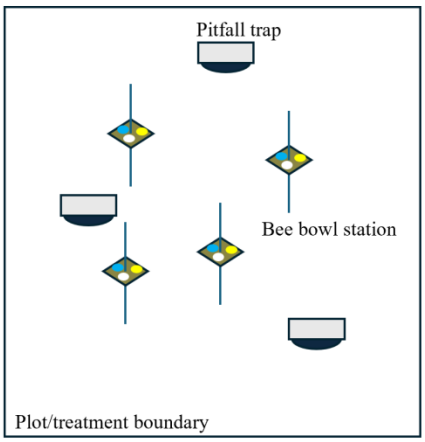


Figure 3-5. Diagram of pitfall traps and bee bowl stations set up in a field.

To ensure these methods were feasible for the study area, insect sampling methods were used that required only basic materials and included no subjectivity in data collection. The bee bowl trap consisted of a blue, yellow, white cup, containing soapy water, and were held in place on a white plastic corrugated board stand suspended on a wooden pole (Figure 3-6; Carkner et al., unpublished). White and yellow plastic cups, 50 ml in size, were sourced from General Plastics in Nairobi. The blue plastic cups were created by spray painting white cups blue. Three larger holes were cut out from a square piece of 20 cm white corrugated plastic board, and one smaller hole was cut so that the platform could be attached to the pole. The three larger holes were cut so that the painted cups could be placed inside with a small lip remaining above the platform.

To set up the bee bowl trap was established by pushing a wooden stake, often just a stick sourced from the farm, into the ground. The white plastic platform was pushed onto the pole and was positioned at the height of surrounding vegetation. The three cups (one of each colour) were placed into the three large holes cut into the corrugated plastic board. A solution of water and soap was mixed consisting of 4 L of

water to 1 teaspoon/5 mL of unscented liquid dish soap. The three cups were filled 3/4 full of the soap water solution.

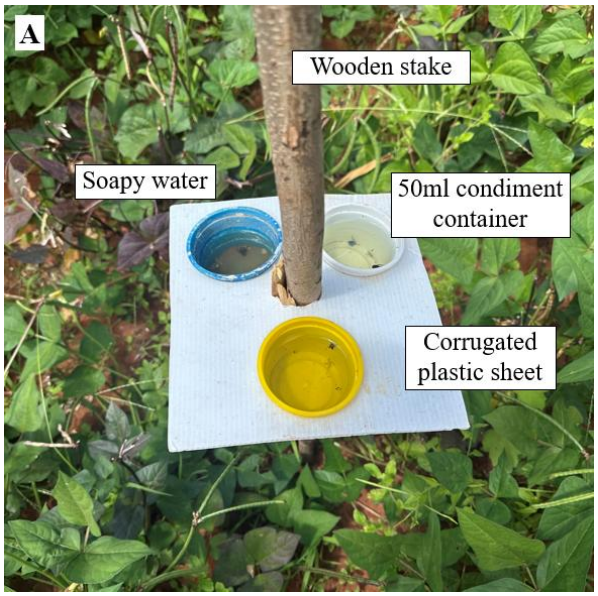


Figure 3-6. A bee bowl trap set up in a field.

Pitfall traps were used to capture ground-based insects. The traps consisted of a plastic container dug into the ground. Chicken wire and a plastic cover were used to exclude rain and sunlight. To set up the trap, a hole was dug into the soil large enough to fit a 1.4 L plastic container. Soil was repositioned so that the container was flush to the ground and disturbed residue was replaced. A piece of chicken wire was laid flat over the container and flush with the ground to exclude larger animals. Then nails were placed in corners of the white 15 × 15 cm corrugated plastic square and were driven into the soil at slight angles. This helped ensure the chicken wire laid flat. A gap of at least 4 cm between the soil and the rain/sunlight cover was left to allow ample space for insects to access the trap (Figure 3-7; Carkner et al., unpublished).

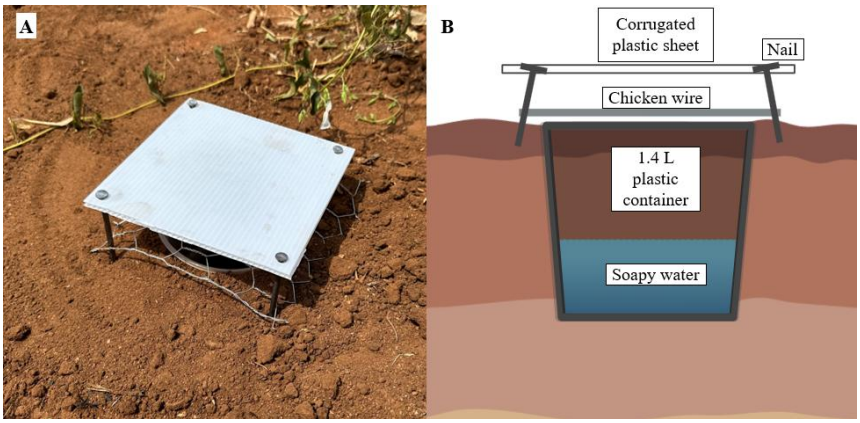


Figure 3-7. (A) In field example of a set up pitfall trap and (B) and labeled cross section of the trap in the ground.

After 48 hours, insects were collected from both the pitfall and bee bowl traps. The soapy water containing the insects was poured through a fine meshed strainer. An extra cup was placed under the strainer to catch water. This water could be used to rinse off the insects if they were muddy. Using a pair of forceps, insects were picked up by the base of the wing, or leg, or optionally by the thorax in the case of large insects and placed into a labeled watertight plastic bag. Surgical spirits (70% ethanol) where added to preserve the insects, enough was added to ensure they were fully covered in the bags. Samples were sent to South Eastern Kenya University to be counted and identified to the order taxonomic level.

3.3.3.3 Focal Farm Dataset

Baseline Soil Samples

Soil samples were collected on November 20th and November 21st, 2024, using a Royal Eijkelkamp auger (model # 04.06.01) with a diameter of 13 mm. Samples were taken to a depth of 20 cm in six locations randomly selected across the field. Samples were combined and placed in a labeled plastic bag. Additionally, bulk density samples were taken at three locations per plot corresponding to three of the six soil sampling locations. A metal cylinder with a known volume was hammered in to the soil profile horizontally at a depth of 10 cm. Then the metal cylinder was carefully excavated. On November 22nd, 2024, the samples were taken to Kenya Agriculture and Livestock Research Organization (KARLO)

for soil nutrient, pH, SOC, and bulk density analysis. Accurate phosphorus data could not be obtained from the baseline samples. The lab used different methods of phosphorus analysis between treatments within farms despite relatively small differences in pH. When pH was less than seven, the Olsen test was used. When pH was greater than seven, the Mehlich test was used. All Olsen tests returned values of 'trace' even though Mehlich values ranged between 18 and 67 PPM. Based on these irregularities, phosphorus results were not included in the results.

Ground Cover

Ground cover was measured three times per growing season: early in the growing season, middle of the growing season, and late in the growing season. Measurements were taken over three growing seasons beginning in November of 2024 and ending in February 2026. Sampling dates are shown on Table 3-4 below. Four locations were randomly selected in each field roughly following a 'Z' shaped sampling pattern. A measuring tape was extended to five metres in a random direction on the field. In cases where clear rows where discernible, the sampling line was laid out perpendicular to the rows. Plant material was considered to cover the soil if it was within approximately 10cm of the soil surface. Looking from directly above, at each 10cm mark, an observation was made to assess if the soil surface was visible or if it was obstructed by plant material. Over the five metres, this totaled 50 observations. Multiplying this value by two yielded the percent ground cover.

Table 3-3. Dates of ground cover measurements, across nine sampling periods.

	Date of sample collection								
Farm number	Early S1	Mid S1	Late S1	Early S2	Mid S2	Late S2	Early S3	Mid S3	Late S3
1	20-11-2024	22-01-2025	19-03-2025	26-04-2025	19-05-2025	08-12-2025	12-09-2025	13-01-2026	19-03-2026
2	20-11-2024	22-01-2025	19-03-2025	26-04-2025	19-05-2025	08-12-2025	12-09-2025	13-01-2026	19-03-2026
3	21-11-2024	23-01-2025	21-03-2025	26-04-2025	20-05-2025	08-05-2025	12-10-2025	14-01-2026	20-03-2026
4	21-11-2024	23-01-2025	21-03-2025	26-04-2025	20-05-2025	08-05-2025	12-10-2025	14-01-2026	20-03-2026

Biomass Samples

Samples of herbaceous biomass (including plant litter) were collected by randomly selecting four locations in each treatment and removing all herbaceous biomass and plant litter in a 0.25m^2 quadrat. Detailed descriptions of sampling procedures are found in Appendix C. Samples were taken twice per growing season over two growing seasons and once during the third growing season. The first sampling period occurred on January 22nd, 2025. Subsequent dates of biomass sample collection are listed in Table 3-4. Biomass samples were then placed in a paper bag and allowed to air dry to ambient moisture levels. The partner staff sent these samples to South Eastern Kenya University to be oven dried and weighed. Given the small capacity of the available oven, samples were packed in densely. To ensure even drying, samples position in the oven was mixed approximately every 1-2 hour during the staff's eight-hour workday. Samples were oven dried for 24 hours at 75 ℃ then weighed.

Table 3-4. Dates of herbaceous biomass sampling, across five sampling periods.

	Date of sample collection				
Farm number	Mid S1	Late S1	Mid S2	Late S2	Mid S3
1	22-01-2025	19-03-2025	17-05-2025	08-12-2025	20-01-2026
2	22-01-2025	19-03-2025	17-05-2025	08-12-2025	20-01-2026
3	23-01-2025	21-03-2025	18-05-2025	08-05-2025	21-01-2026
4	23-01-2025	21-03-2025	18-05-2025	08-05-2025	21-01-2026

Focal Farm Insect Samples

Insects collected as part of the focal farm dataset employed bee bowls and pitfall traps using the same materials as listed in the methodology section for the insect dataset. Insect samples on these four farms were collected over 8 sampling periods (Table 3-5), as with the larger insect data. Four bee bowl stations and three pitfall traps were established per field. Insects were sent to South Eastern Kenya University and were identified to the family level. Spiders (Araneae) were not identified to the family level but were counted and were included in the data as a singular taxonomic group. Due to

miscommunication with the entomologist during the first six sampling periods, only richness data was recorded. For the last two sampling periods, the abundance of insect species was recorded as well.

Table 3-5. Dates of insect sampling, across eight periods. Under each heading the first date denotes the date the traps were set out, and the second date indicates when the insects were collected

	Date of sample collection			
Farm number	Early S1	Mid S1	Late S1	Early S2
1	04/12/2024 - 06/12/2024	13/01/2025 - 15/01/2025	15/03/2025 - 17/03/2025	22/04/2025 - 24/04/2025
2	04/12/2024 - 06/12/2024	09/01/2025 - 11/01/2025	15/03/2025 - 17/03/2025	22/04/2025 - 24/04/2025
3	05/12/2024 - 07/12/2024	13/01/2025 - 15/01/2025	18/03/2025 - 20/03/2025	21/04/2025 - 23/04/2025
4	05/12/2024 - 07/12/2024	13/01/2025 - 15/01/2025	18/03/2025 - 20/03/2025	21/04/2025 - 23/04/2025
	Mid S2	Late S2	Early S3	Mid S2
1	13/05/2025 - 15/05/2025	09/08/2025-11/08/2025	09/12/2025 - 11/12/2025	10/01/2026 - 12/01/2026
2	14/05/2025 - 16/05/2025	09/08/2025-11/08/2025	04/12/2025 - 06/12/2025	10/01/2026 - 12/01/2026
3	14/05/2025 - 16/05/2025	04/08/2025-06/08/2025	02/12/2025 - 04/12/2025	13/01/2026 - 15/01/2026
4	14/05/2025 - 16/05/2025	04/08/2025-06/08/2025	03/12/2025 - 05/12/2025	11/01/2026 - 13/01/2026

3.3.4 Statistical Analysis

3.3.4.1 Soil dataset

Differences between treatments for Solvita tests, hoe test, slakes test, and water infiltration score were assessed using paired sample *t*-tests as each farm contained one BAU and FMNR plot. Normality of the data was assessed by plotting the differences between treatment values at each farm on a qq plot. If there was doubt as to the normality of the data, a Wilcoxon rank-sum test was also run. In no cases did this cause any results to become non-significant. The paired data structure and differences between treatments on each farm were plotted. A linear model was created to assess the relationship between the farmer led subjective hoe test and the objective Solvita test.

3.3.4.2 Insect dataset

For the insect data, diversity was calculated along Hill numbers (q = 0, 1, 2) to assess frequencies and distributions of taxonomic groups (Hill 1973; Jost 2006). As q increases from 0, the index becomes

less sensitive to rare taxa and more sensitive to dominant taxa. At q = 0, all taxonomic groups have the same weighting, and the value is independent of their abundance (i.e. richness). At q = 1 the calculated value represents the exponential of Shannon entropy. At q = 2 (inverse Simpson) the index increasingly favours evenness and becomes less sensitive to rare taxa. This framework expresses diversity in common units and converts values into an interpretable scale. Hill numbers were calculated in R using the package *hillR* (Li 2018). Treatment differences between hill numbers q = 0, 1, and 2 were assessed using paired sample t tests, as above. Normality was assessed using qq plots. The equation below depicts how hill numbers are calculated for values of q (Jost 2006):

$$ {}^{q}D = \left(\sum_{i=1}^{S} p_i^q \right)^{1/(1-q)} $$

Where p_i is the relative abundance of species/taxa *I,* q is the order of diversity and dictates the sensitivity to abundance, and S is the total number of species/taxa.

Additionally, to assess if trap type had an influence on treatment effects, we separated the sampled insects into two groups: insects captured in pitfall traps and, insects captured in bee bowls. Using the same methods as mentioned above, hill numbers were calculated and differences assed using paired sample t tests.

3.3.4.3 Focal farm dataset

Baseline soil tests between the two treatments were compared using paired sample *t*-tests for each variable between BAU and FMNR farms. Normality was assessed using qq plots.

Average biomass kg ha^{-1} and ground cover measured as a percent were calculated and plotted for visualization. Then for biomass and ground cover measurements a mixed linear model was produced using the *Lme4* package (Bates et al. 2015). Model parameters included treatment, growing season, and the interaction between season and treatment as fixed effects. Farm was included as a random effect to account for repeated measures and allowed intercept to vary between farms. Statistical significance of the

fixed effects was assessed using type III analysis of variance, with Satterthwaite's approximation for degrees of freedom, using the *lmerTest* package (Kuznetsova et al. 2017).

Statistical tests were not performed for the focal farm insect data given the low number of farms involved (n=4), rather, descriptive statistics were used. Data were summarized by order and family and any large differences in mean counts were noted. Bray-Curtis dissimilarities were calculated for the three dominant orders, Coleoptera, Diptera, and Hymenoptera (Banks et al., 2022) using the *vegan* package (Dixon, 2003). Hill numbers were calculated from $q = 0$ to $q = 3$ on 0.1 increments and graphed for the FMNR and BAU treatments. Family level richness was assessed for across eight sampling periods; data was graphed for each farm separately.

3.4 Results and discussion

3.4.1 Soil Dataset

Utilizing the first sampling period of data, paired sample t tests were performed to compare the slake test for aggregate stability including Solvita tests for microbial respiration, the hoe test, and water infiltration score. Mean slake test scores of the FMNR plots did not significantly differ from BAU plots (Table 3-6; Figure 3-8). Similarly, no differences were seen in the second period of sampling (Table 3-7; Figure 3-9). Given the short period of time from treatment establishment to measurement, the lack of a significant effect was not surprising. Most of the factors that influence aggregate stability in this landscape, including minerology, texture, and cation composition are not expected to change in the short-term, if at all, in response to the treatment. While soil carbon can influence soil aggregate stability (Almajmaie et al. 2017), it is unlikely that any meaningful changes in soil carbon occurred after two or three growing seasons. Additionally, concentrations of labile forms of soil organic carbon (SOC), a form of SOC that develop over short periods of time, have not been observed to relate to aggregate stability (Almajmaie et al. 2017).

Table 3-6. Results from paired sample t tests taken in April-May 2025, for four soil health parameters.

Variable	FMNR mean	FMNR SD	BAU mean	BAU SD	t statistic	df	P value
Hoe test	2.84	1.14	1.92	1.00	4.82	24	>0.001
Slake test	0.53	0.22	0.56	0.22	-0.62	23	0.541
Solvita test	1.97	1.12	1.61	0.97	2.54	24	0.018
Water infiltration	3.12	1.05	2.20	1.22	3.87	24	0.001

Table 3-7. Results from paired sample t tests taken in December 2025, for four soil health parameters.

Variable	FMNR mean	FMNR SD	BAU mean	BAU SD	t statistic	df	P value
Hoe test	3.40	0.65	2.52	0.59	6.06	24	0.000
Slake test	0.54	0.15	0.53	0.14	0.38	24	0.705
Solvita test	2.34	0.81	1.96	0.83	2.02	24	0.054
Water infiltration	3.56	0.51	2.40	1.04	6.15	24	0.000

There is also a possibility that there may have been underlining differences in history of erosion between the two treatments. Past erosion may have altered remaining topsoil. Therefore, there may have been differences in initial aggregate stability prior to measurement confounding the measurements taken. The lack of proper baseline samples combined with the expected placement of FMNR on degraded land adds a challenge to identifying differences in aggregate stability. Visible severe erosion was observed in the BAU treatment of one farm (one of four personally visited), while erosion in the FMNR treatment on the same farm appeared minor. Therefore, it is unclear if FMNR plots were on average more degraded at baseline. It would have been beneficial to collect reports from the farmer on their perceptions on the relative condition of the two treatments on their farm.

Solvita test for soil respiration

In the first period of sampling, mean Solvita test values for the FMNR plots were significantly higher compared to the BAU plots (Table 3-6; Figure 3-8). In the second period of data collection FMNR plots had higher mean Solvita test values, but the difference was marginally significant ($p = 0.054$, $t =$

2.02; Table 3-7; Figure 3-9). These results indicate that microbial soil respiration and carbon mineralization were higher in the FMNR treatment compared to the BAU treatment. The higher microbial activity and associated carbon mineralization are associated with higher nutrient cycling (Gan et al., 2020) and are early indicators for changes to soil health (Crookston et al. 2023). To the author's knowledge, no assessments of soil respiration have previously been performed specifically in FMNR plots.

Microbial activity in soil is also important for the formation of stable forms of organic matter, such as mineral associated organic matter, which is resistant to decomposition. Mineral associated organic matter often forms from microbial necromass (Kallenbach et al. 2016). Higher soil respiration/microbial activity has also been shown to be proportional to soil organic carbon content (Gan et al. 2020), but after just two growing seasons of treatment implementation, it is very unlikely that this difference in carbon content is responsible for the higher observed soil respiration. Instead, the observed treatment effect may be caused by priming, which results in a change in the mineralization rate of native soil organic carbon following the addition of new organic substances (Kuzyakov 2010). This process is mediated by microbial responses to carbon and the nutrient availability within the soil (Kuzyakov 2010). If the higher carbon inputs in the FMNR treatment can be maintained, it is expected that soil organic carbon would increase in the long term (Feng et al. 2022).

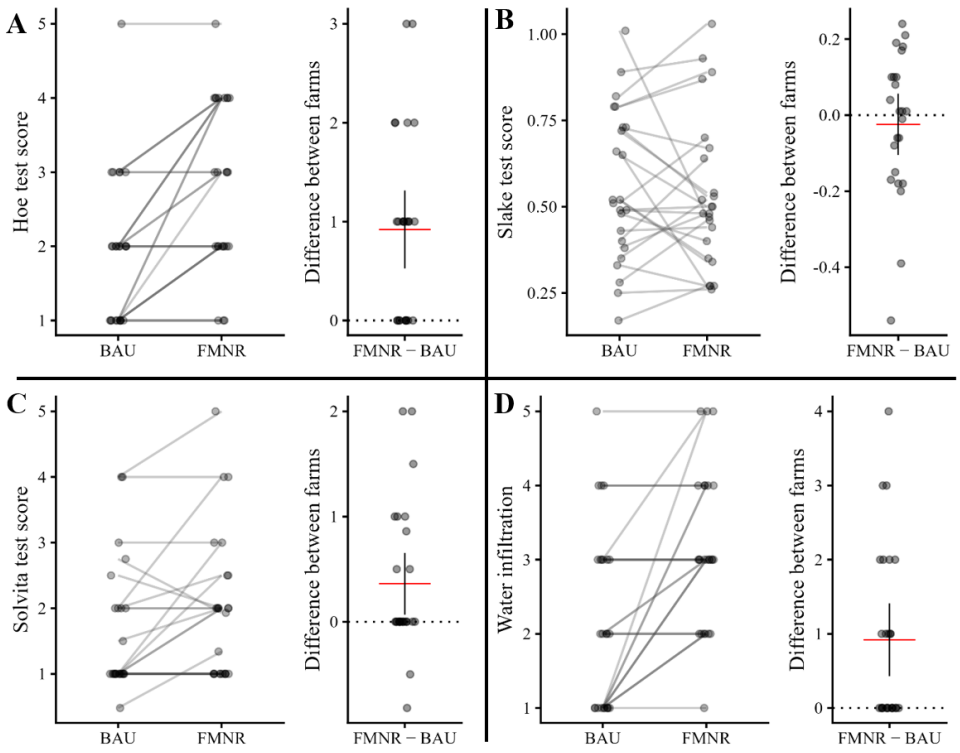


Figure 3-8. Results from 21 farms taken in April-May 2025**.** Results of hoe test (A), Slake test (B), Solvita test (C) and Water infiltration score (D). One the left graphs of each panel the line between points shows the difference between BAU and FMNR treatments within a farm. The right graph on each panel shows differences between paired farm data. The horizontal red line represents the mean and the vertical black line represents the 95% CI.

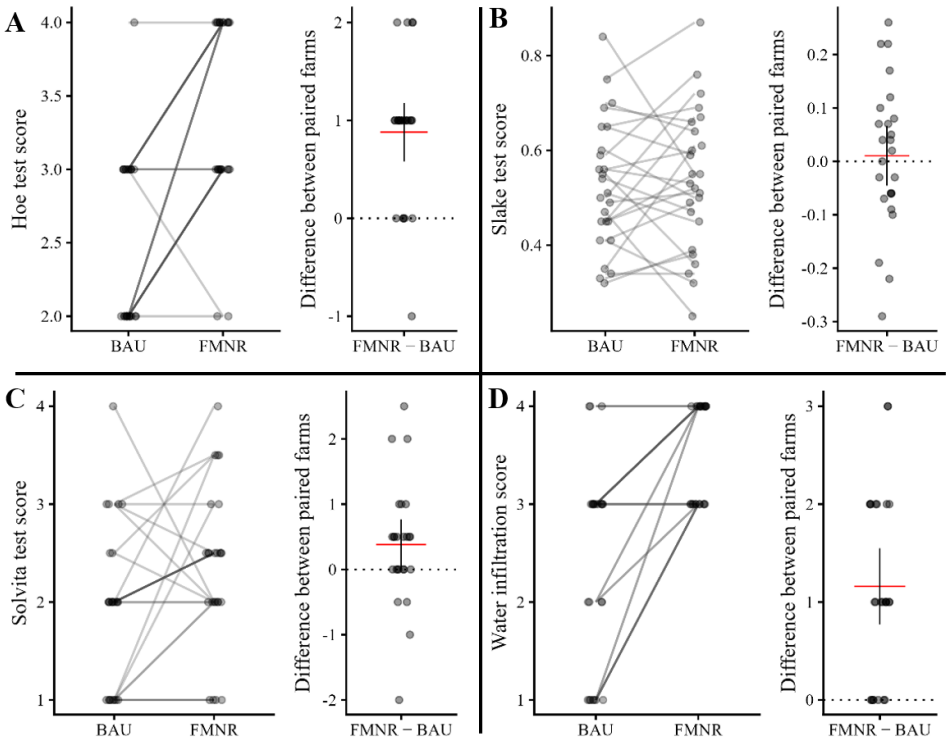


Figure 3-9. Results from 21 farms taken in December 2025**.** Results of hoe test (A), Slake test (B), Solvita test (C) and Water infiltration score (D) (left graphs on each panel). The right graph on each panel shows differences between paired farm data and the line between points shows the change between treatments within a farm. The horizontal red line represents the mean and the vertical black line represents the 95% CI.

Hoe test and water infiltration score

In both the first (Table 3-6; Figure 3-8) and second sampling period (Table 3-7; Figure 3-9), paired sample *t*-tests showed that among the 25 sampled farms, the mean hoe test score was higher in FMNR plots than in BAU plots. Paired sample t tests were also performed for water infiltration scores. Mean values for the FMNR plots were significantly higher compared to the BAU plots. These results are shown on Table 3-6 and Figure 3-8 for the first sampling period and Table 3-7 and Figure 3-9 for the second sampling period. Elsewhere in Kenya, farmers have used these two tests to identify improvements in agriculture systems (Entz et al. 2022). These results suggest higher friability, soil structure, and improved water access for plants. These differences may have been driven by the higher ground cover and

the herbaceous biomass (discussed below). Our results reinforce the ability of these tests to help farmers identify changes on their farm in response to practices they implement.

The ability of farmers to perceive changes to soil fertility have been associated with increased propensity to adopt improved practices (Spurk et al. 2025), highlighting the value of the farmer observed improvements. The hoe test was originally implemented in conservation agriculture systems (Entz et al. 2022). Farmers may face difficulty hoeing in FMNR systems due to the presence of tree roots, but this was not raised as a concern by farmers in this study. The demonstrated ability to still work the soil may help facilitate adoption of FMNR agroforestry systems integrated with annual crops.

Despite the strong results from the hoe test and water infiltration score, the results warrant some caution. There were zero instances of FMNR plots being rated lower compared to the BAU plots for both the hoe test and water infiltration score in the first sampling period (Figure 3-8. Only in one instance was FMNR rated poorer than the BAU plots in the second sampling period. This does raise concerns of potential expectancy bias. To help address this concern, a linear model was created to assess the relationship between the Solvita test for soil respiration and hoe test scores taken during the first sampling period. Results revealed that hoe test scores increased linearly with Solvita test scores. The fitted regression model was y = 0.82 + 0.41x. The overall regression was statistically significant ($R^2 = 0.202$, $F_{1, 24} = 12.17$, $P = 0.001$); (Figure 3-10).

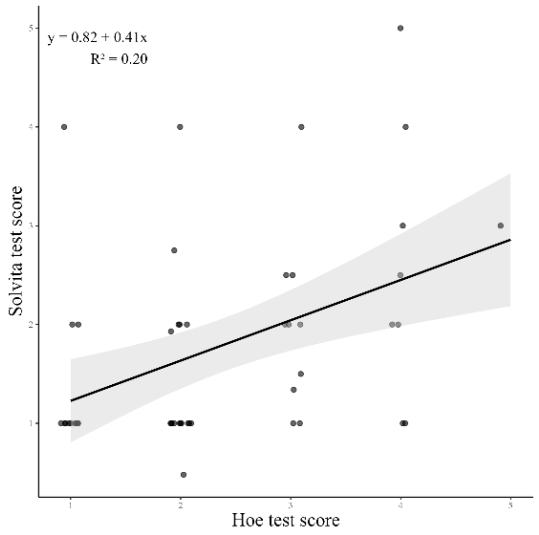


Figure 3-10. Linear model between Solvita soil respiration test and hoe test scores across sampled farms (n = 50). Points represent individual observations and they are jittered to reduce overlap. The solid line shows the fitted linear regression, and the grey band represents the 95% CI.

The significant positive relationship between hoe test scores and soil respiration scores (Solvita) suggest farmers are identifying some tangible differences using the hoe test, thus supporting the validity of this test. The R^2 value was low (0.202), although this was expected. The two tests measure very different aspects of soil health. One measures CO_2 respiration, the other measures farmer perceived changes in soil structure and quality. Supporting the findings of (Entz et al. 2022), we demonstrate the potential of these participatory soil health tests to evaluate soil changes.

Taken together, the positive impact of FMNR on soil respiration, soil structure, water infiltration measured through the hoe-test, and water infiltration score, support existing farmer perceptions that FMNR increases soil health (Kibru et al. 2021; Camara et al. 2023; Yiridomoh et al. 2024). Collectively, the results of the soil tests support our hypothesis of improved soil health and more broadly of FMNRs contribution to agroecosystem resilience.

3.4.2 Insect Dataset

From sampling on 21 farms, a total of 736 insect specimens were collected in the BAU compared to 749 in the FMNR plots. Hymenopterans were dominant in both treatments and especially in the BAU treatment. Based on additional insect results from four farms (focal farm dataset), it is likely a large majority of these Hymenopterans belonged to the family Formicidae (ants). There were notable mean differences in coleopteran abundance between the two communities with 230 specimens having been captured in the FMNR plots compared to 114 being captured in the BAU plots. Bee bowls appeared to have captured higher counts of specimens compared to the pitfall traps (**Table 3-8**).

Table 3-8. Summary of insect orders collected on 21 farms.

BAU			FMNR		
Order	Bee bowl	Pitfall	Order	Bee bowl	Pitfall
Hymenoptera	296	227	Hymenoptera	207	184
Coleoptera	104	10	Coleoptera	196	34
Diptera	53	2	Diptera	56	10
Lepidoptera	32	1	Lepidoptera	42	6
Orthoptera	0	11	Orthoptera	0	14
Total	*485*	*251*		*501*	*248*

When all samples were aggregated together, there was no significant difference between FMNR and BAU richness ($q = 0$) (Wilcoxon signed-rank test: $V = 45.5$, $P = 1$). At $q = 1$ there were marginally significant differences between the FMNR and BAU treatment; $t(29) = 1.867$, $P = 0.077$ At q = 2, the FMNR treatment had a significantly higher mean effective number of orders (mean = 2.333, SD = 0.596) compared to the BAU treatment (mean = 1.956, SD = 0.518); $t(20) = 2.397$, $P = 0.0264$. There appeared to be a divergence between treatments at higher orders of diversity (Figure 3-11).

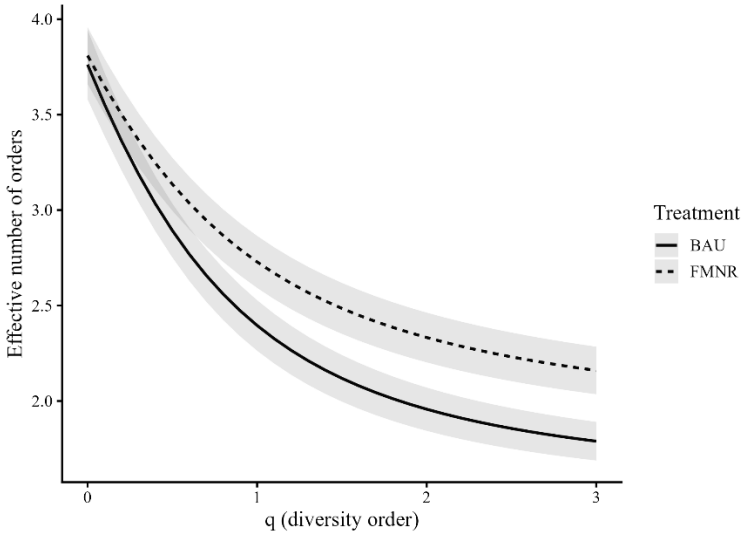


Figure 3-11. Diversity profile as a function of order *q* of the BAU treatment (solid line) and FMNR treatment (dashed line). The light gray band represents ± SE.

When considering only specimens captured in pitfall traps at q = 0, the effective number of orders was significantly higher in the FMNR treatment (mean = 2.381, SD = 0.740) compared to the BAU treatment (mean = 1.571, SD = 0.676); $t(20) = 3.783$, $P = 0.001$. Similarly, at q = 1, the effective number of orders was again significantly higher in the FMNR treatment (mean = 1.827, SD = 0.618) compared to the BAU treatment (mean = 1.279, SD = 0.375); $t(20) = 3.360$, $P = 0.003$. At q = 2, the effective number of orders was significantly higher in the FMNR treatment (mean = 1.622, SD = 0.565), compared to the BAU treatment (mean = 1.191, SD = 0.262); $t(20) = 3.047$, $P = 0.006$. The relationship between effective number of orders, treatment, and trap type is depicted on Figure 3-12.

When considering specimens captured in bee bowls, no significant differences between FMNR and BAU treatments were observed at any of $q = 0$, 1, or 2 (Table 3-9). The relationship between effective number of orders, treatment, and trap type is depicted on Figure 3-12.

Table 3-9. Summary of t test results for bee bowl traps at q = 0, 1, and 2.

Hill number (q)	Mean difference (FMNR − BAU)	t (df)	P-value	95% CI
q = 0	-0.238	-1.00 (20)	0.329	[-0.735, 0.259]
q = 1	-0.100	-0.46 (20)	0.650	[-0.551, 0.351]
q = 2	-0.075	-0.36 (20)	0.723	[-0.509, 0.360]

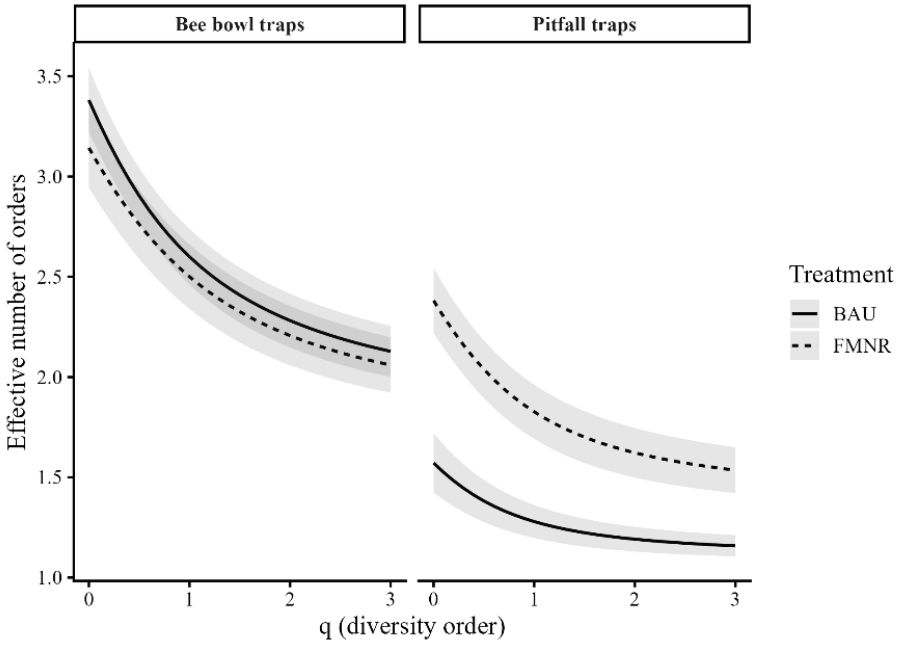


Figure 3-12. Diversity profiles as a function of q for the BAU (solid line) and FMNR (dashed line) treatment. The left panel includes specimens only captured in bee Bowl traps while the right panel considers only specimens captured in pitfall traps. The light gray band represents ± SE.

Our results indicate that most treatment effects were being detected amongst specimens captured in pitfall traps. The insect dataset results overall, support our hypothesis of higher diversity and resilience in the FMNR treatment. To our knowledge this represents the first quantitative evidence for the impacts of FMNR on insect communities.

Other studies have highlighted the importance of trees in landscapes to support insect biodiversity. For example, in Malawi, farmland had roughly half the species richness as compared to surrounding woodlands (Vogel, Mayer, et al. 2023). As the FMNR plots continue to develop, the establishing trees in the FMNR plots may offer future benefits like those seen in Malawi (Vogel, Mayer, et al. 2023). In northern Tanzania, agroforestry has been shown to play an important role in supporting both insect abundance and diversity (Kingazi et al. 2025). Insect abundance during the dry season was twice as high in the agroforestry system compared to the non-agroforestry farms. Flower richness, plant richness, and overall plant abundance were determined to drive these higher abundances. An increase in abundance in the present study was not seen despite periods of higher biomass (Kingazi et al. 2025).

There are several explanations for the lack of treatment effects observed with the bee bowls. Bee bowls mostly capture flying, highly mobile insects. Additionally, the habitat quality of the surrounding landscapes can have a large impact on population of certain insects such as pollinators (Kennedy et al. 2013). Therefore, insects trapped with plots to some extent also represent populations of the broader landscape and the neighbouring treatment, obfuscating potential treatment effects behind increased variability.

Additionally, the treatments potentially had two contrasting effects on the flying insect counts. First, if the plant composition within FMNR plots is more appealing to pollinators and other insect functional groups, it would be expected that more flying insects are caught in the FMNR plot compared to the BAU plot. However, if the BAU plots have poor plant communities and with low ground cover, the bee bowls may be more visible to pollinators and therefore may have higher counts. These two competing effects may have influenced results in the present study.

For pitfall data, the higher effective diversity in FMNR plots compared to BAU plots may be related to the higher ground cover and herbaceous biomass sampled on the four intensively monitored farms. Both biomass and ground cover have been shown to affect crawling insect assemblages in various

contexts. For example, Banks et al., (2022) observed that bare ground was associated with lower beetle diversity. Other authors have highlighted the positive relationship between live plant biomass and Hymenoptera diversity (Symstad et al. 2000). In other settings, cover crops have been shown to increase the abundance of predators, parasitoids, and phytophagous insects (Sáenz-Romo et al. 2019). However dead plant ground cover can also reduce observed abundance (Banks et al. 2022) potentially due to reduced insect mobility.

The bee bowl methodology faced several problems in this research context. Given the arid environment, animals were attracted to the water in the bee bowl cups. Farmers reported both livestock and wild birds drinking from the cups. Evidence of birds visiting bowl cups was viewed firsthand (

Figure **3-13**). The fenced FMNR treatments were reportedly less disturbed by livestock than the unfenced BAU treatments. Birds were also observed eating the insects caught in the bee bowls. However, there is no identifiable reason why this may have impacted one treatment more than the other. Due to these disturbances combined with the heat and sun, bee bowls were frequency found to be dried up inhibiting the ability of the bee bowls to capture insects.



Figure 3-13. Bird droppings on bee bowls left by visiting birds.

3.4.3 Focal Farm Dataset

3.4.3.1 Baseline soil samples

Results from soil samples taken on four farms revealed no underlying differences in measured soil metrics shortly after treatments began. Accurate phosphorus data could not be obtained from the baseline samples. There were no significant differences between any of the soil treatments (paired sample t test). There was a marginally significant difference in soil pH values between the two treatments but since mean pH values were both close to neutral there is little biological relevance to this difference (Table 3-10).

Table 3-10. Paired sample t tests for baseline soil test variables between BAU and FMNR treatments. No Significant differences were found between treatments.

Variable	BAU (SD)	FMNR (SD)	Estimate	*P* value
Soil pH	6.71 (0.60)	6.95 (0.53)	-0.24	0.053
Total Nitrogen %	0.13 (0.05)	0.10 (0.02)	0.03	0.302
Total Org. Carbon %	1.32 (0.44)	1.01 (0.18)	0.31	0.293
Potassium meq%	0.64 (0.45)	0.79 (0.40)	-0.15	0.631
Calcium meq%	11.00 (8.14)	10.45 (4.25)	0.55	0.893
Magnesium meq%	6.11 (0.43)	5.92 (0.30)	0.19	0.491
Manganese meq%	0.23 (0.03)	0.20 (0.17)	0.04	0.654
Copper ppm	3.51 (1.98)	3.83 (1.08)	-0.32	0.615
Iron ppm	25.96 (13.96)	27.39 (15.87)	-1.42	0.863
Zinc ppm	26.92 (22.61)	20.14 (11.35)	6.77	0.618
Sodium meq%	0.18 (0.15)	0.15 (0.07)	0.03	0.623

Therefore, results of the present study demonstrate that, despite some visual differences between FMNR and BAU plots prior to treatment establishment, there were no differences observed between treatments at the start of the experiment.

3.4.3.2 Ground cover and biomass

Based on the results of a linear mixed model, FMNR plots had significantly higher ground cover compared to the BAU plots ($F_{1,55} = 78.78$, $P < 0.001$). Season had no effect ($F_{2,55} = 1.24$, $P = 0.298$) and the treatment season interaction was marginally significant ($F_{2,55} = 2.77$, $P = 0.071$). At the early S1 sampling period, mean ground cover in the FMNR plots was approximately 56% compared to a mean of 44% in the BAU plots. In season two, mean ground cover rose notably in the FMNR plots reaching 68% at mid season. In contrast mean ground cover in BAU plots were observed to decrease over the course of season reaching a low of 32%. By middle of season, three ground cover plots converged slightly to 60% for FMNR and 38% for BAU (Figure 3-14).

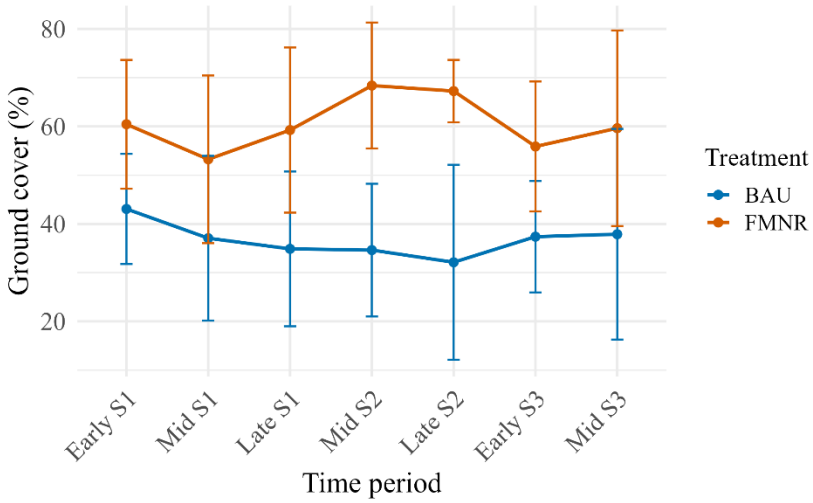


Figure 3-14. Mean ground cover measured at sampling periods over three growing seasons. Error bars represent SD.

The higher ground cover observed in FMNR plots has implications for soil moisture conservation. Soil moisture conservation is particularly important in semi-arid regions, including the present study area. Ground cover is an effective way to reduce evaporation the limited water loss from the soil (Demo and Asefa Bogale 2024). Plant residues lower the temperature of the soil (Abdallah et al., 2021), reduce wind speeds over the soil surface (Fuchs and Hadas 2011), and physically block soil air contact, which all contributes to lower rates of evaporation form the soil surface. The more abundant and longer lasting soil moisture can help to reduce the severity and length of periods of moisture stress.

Soil erosion is wide spread in the region (Lohbeck et al. 2018). A prominent cause of erosion is due to water run off (Blake et al. 2018). The increased soil cover facilitated by FMNR can help reduce the speed of water across the soil surface (Kihara et al. 2020) thereby reducing the erodibility of the landscape. This was observed by (Lohbeck et al. 2018) at a nearby landscape with in Kitui County Kenya where lower ground cover was associated with higher prevalence of severe erosion. Additionally, they observed sites where higher ground cover was associated with higher soil organic carbon. The increased ground cover measured in FMNR plots may have provided similar benefits as cited above. The increased

ground cover supports our hypothesis of FMNR plots increasing resilience even after only two growing seasons. Future research should explore this topic further.

Our ground cover measurement did not distinguish between living and dead plant matter. While this was done for simplicity, separating living plants and plant litter would have helped identify between plants reestablishing (living portion) and stockpiling of plant biomass (living + dead portion). This is also relevant in the relation to insect biodiversity, as living vs dead ground cover can have contrasting effects on insect communities (Banks et al. 2022).

There is some discussion in the literature pertaining to the impacts of ground cover on seedling establishment. One meta-analysis concerning grasslands noted that litter may have positive effects on seedling establishment under dry conditions and at low to medium litter amounts (corresponding to 500 g m^{-2}). The authors also noted that large seeds had higher rates of establishment under plant litter (Loydi et al. 2013). This is particularly relevant within discussion of FMNR as many of these landscapes are degraded with significant bare patches of soil. Enrichment planting of grasses may be utilized in these systems to help restore plant growth; its use was seen on several plots alongside FMNR in our study. No studies have assessed the impacts of ground cover on the establishment of seeds in FMNR systems. Future studies should seek to explore this interaction. Studies could examine the effects of supplementing areas with residues gathered elsewhere to facilitate establishment of plants in sparse or bare areas. This short-term cost may help accelerate the returns from FMNR. The interaction between supplemented ground cover and enrichment planting of grasses is also likely species dependent.

At the start of the experiment, mean sampled herbaceous biomass was 694 kg ha^{-1} for the FMNR treatment and 574 kg ha^{-1} for BAU. Mean biomass values decreased in the middle of season two to 577 kg ha^{-1} for FMNR and 357 kg ha^{-1} for BAU, before increasing late in the second growing season to 1010 kg ha^{-1} and 503 kg ha^{-1} for FMNR and BAU respectively. In season three, biomass declined sharply in the FMNR treatment falling to 518 kg ha^{-1} (Figure 3-15).

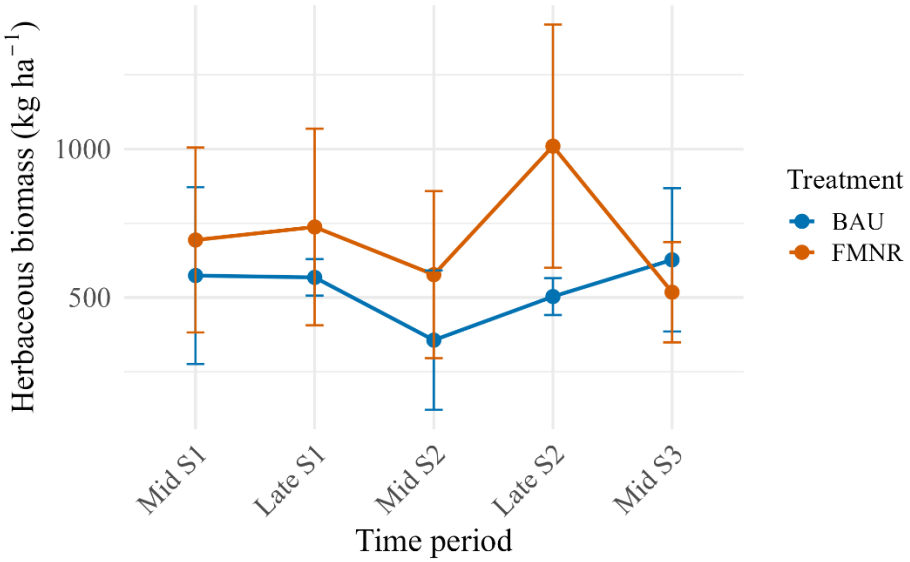


Figure 3-15. Mean herbaceous biomass (kg ha^{-1}) sampled over three growing seasons (S1, S2, S3). Error bars represent SD.

Across all sampling periods there was marginal evidence that FMNR increased herbaceous biomass ($F_{1,31}$ = 2.88, P = 0.100). Season had no significant effect ($F_{2,31}$ = 0.25, P = 0.783). The treatment season interaction was marginally significant ($F_{2,31}$ = 2.77, P = 0.078).

However, when considering only herbaceous biomass samples from season one and season two, biomass was significantly higher in the FMNR treatment compared to the BAU treatment ($F_{1,25}$ = 9.15, P = 0.006). Neither season ($F_{1,25}$ = 0.14, P = 0.710) nor the treatment season interaction ($F_{1,25}$ = 1.70, P = 0.205) were significant.

The sharp decline in herbaceous biomass observed in the FMNR treatment in the third season was reportedly due to grazing. November is the wettest month on average (Figure 3-2), yet rainfall in November 2025 was far below normal (

Figure **3-3**). Local project partners reported that these delayed rains led to farmers to utilizing the fodder stored in FMNR plots.

This observation highlights the opportunity of FMNR to maintain a store of resources that can be accessed during times of need and highlights FMNRs capacity to increase system resiliency. Examples from literature show similar instances of farmers utilizing FMNR to build a stockpile of fodder and tree products (Kuyah et al. 2023). In Ethiopia farmers were able to utilize fodder produced from FMNR within one year (Brown et al. 2011), a similar time frame to our study.

Herbaceous biomass samples peaked at 1010 kg ha^{-1} in the present study. These herbaceous biomass samples are low compared to fodder yield trials in other regions of Kenya. One study looked at shoot dry matter yields of various grass species in Katumani, which receives around 717 mm of rainfall annually, about 70 mm more than the Kitui study location (Gichangi et al. 2017). The study found yields ranged from around 5.5 to 10 t ha^{-1} in the first year of the study and between 2 and 5 t ha^{-1} in the second year (Gichangi et al. 2017). This suggests a large potential for improvement in both the measured FMNR and BAU plots. It is unclear if similar herbaceous biomass yields can be achieved in FMNR systems without seeding grasses as a supplement.

Although the FMNR treatments did have higher sampled herbaceous biomass over some periods of the study, inferences to the relative productivity of the two treatments cannot be made. Both treatments reported some grazing activity, particularly in season three. However, grazing activity was expected to be greater in the BAU plot, resulting in lower biomass remaining for sampling. Understanding the relative productivity of these two treatments overtime would have been extremely beneficial as this would have easily been translated into livelihood benefits and ecological benefits.

Provided FMNR does increase primary productivity, the benefits extend beyond resource partitioning for human use. Increased litter inputs are associated with increased soil organic matter, particularly in the particulate organic matter fraction (Feng et al. 2022). Litter inputs also have the potential to alter C:N ratios which can results in higher carbon accumulation if the litter inputs have higher C:N ratios (Feng et al. 2022). Ultimately, if FMNR can sustain higher primary productivity, it is

expected that soil carbon will increase in the FMNR system as soil carbon sequestration is ultimately regulated by photosynthetic inputs to the soil (Janzen et al. 2022).

3.4.4 Focal Farm Insect Samples

The following results contain only descriptive statistics. In total 994 insect samples were collected in the third season over two sampling periods. Of these, 463 were collected from the BAU treatment and 531 specimens from the FMNR treatment. Hymenoptera dominated the sampled insects in both treatments (Table 3-11), a trend that was driven by very high abundances of Formicidae representing approximately two thirds of the sampled insects (

Table **3-12**). There were several notable numeric differences amongst the abundances of the sampled orders and family. Coleopterans were observed to have higher mean abundances in the FMNR treatment compared to BAU. Additionally, there were notable observed differences between the number of Chrysomelidae sampled in the two treatments with four being identified in the BAU treatment compared to 27 in the FMNR treatment. In other observed Coleopteran families, counts were often low. Only two Carabidae were identified in the BAU treatment compared to one in the FMNR treatment. There were four Staphylinidae in the BAU treatment compared to ten in the FMNR treatment. Three Scarabaeidae specimens were found in the BAU treatment and two in the FMNR treatment.

These results have several potential implications for future studies. The higher overall abundance of Coleopterans observed in the FMNR treatments may be associated with the higher ground cover and biomass observed on these same four farms. Future studies with higher sample sizes could analyze this relationship (Banks et al. 2022). Many Coleopterans can have beneficial impacts in agricultural landscapes. Carabidae species can consume arthropod pests and weed seeds (Cividanes 2021) while dung beetles belonging to Scarabaeidae, aid in incorporating animal dung into the soil and enhance nutrient cycling (Stanbrook and King 2022). Staphylinidae are commonly generalist predators that may offer biological control benefits (Twardowski et al. 2020). Alternatively, some species of Coleoptera may have negative impacts. Many species of Chrysomelidae, such as bean leaf beetles (*Ootheca* spp.) (Lutaakome et al. 2022), are crop pests, but higher counts may also reflect increasing plant diversity and habitat complexity. How the potential observed increase in Chrysomelidae seen in FMNR systems interacts with nearby crops should be a topic of future study.

Table 3-11. Summary of insect order (and Araneae) abundance sampled from four farms each containing a BAU and FMNR treatment. The table includes insects sampled from two sampling periods in the third season of data collection (December 2025 - February 2026). Entries are listed alphabetically.

BAU		FMNR	
Row Labels	Abundance	Row Labels	Abundance
Araneae	38	Araneae	48
Blattodea	5	Blattodea	2

Coleoptera	25	Coleoptera	79
Dermaptera	4	Dermaptera	0
Diptera	35	Diptera	27
Hemiptera	1	Hemiptera	2
Hymenoptera	329	Hymenoptera	352
Lepidoptera	7	Lepidoptera	5
Orthoptera	18	Orthoptera	16
Zygentoma	1	Zygentoma	0
Grand Total	**463**	**Grand Total**	**531**

Table 3-12. Summary of insect family (and Araneae) abundance sampled from four farms each containing a BAU and FMNR treatment. The table includes insects sampled from two sampling periods in the third season of data collection (December 2025 - February 2026). Entries are listed alphabetically.

BAU			FMNR		
Order	Family	Abundance	Order	Family	Abundance
Araneae	NA	38	Araneae	NA	48
Blattodea	Blattidae	5	Blattodea	Termitidae	2
Coleoptera	Buprestidae	4	Coleoptera	Buprestidae	7
Coleoptera	Carabidae	2	Coleoptera	Carabidae	1
Coleoptera	Cerambycidae	2	Coleoptera	Cerambycidae	3
Coleoptera	Chrysomelidae	4	Coleoptera	Chrysomelidae	27
Coleoptera	Dermestidae	4	Coleoptera	Coccinellidae	3
Coleoptera	Elateridae	1	Coleoptera	Curculionidae	5
Coleoptera	Scarabaeidae	3	Coleoptera	Dermestidae	4
Coleoptera	Staphylinidae	4	Coleoptera	Elateridae	4
Coleoptera	Tenebrionidae	1	Coleoptera	Meloidae	1
Dermaptera	Forficulidae	4	Coleoptera	Nitidulidae	1
Diptera	Calliphoridae	1	Coleoptera	Scarabaeidae	2
Diptera	Muscidae	33	Coleoptera	Staphylinidae	10
Diptera	Tabanidae	1	Coleoptera	Tenebrionidae	11
Hemiptera	Reduviidae	1	Diptera	Calliphoridae	3
Hymenoptera	Apidae	15	Diptera	Culicidae	1
Hymenoptera	Chalcididae	2	Diptera	Muscidae	22
Hymenoptera	Formicidae	306	Diptera	Tephritidae	1
Hymenoptera	Vespidae	6	Hemiptera	Reduviidae	2
Lepidoptera	Erebidae	1	Hymenoptera	Apidae	2
Lepidoptera	Noctuidae	2	Hymenoptera	Crabronidae	3
Lepidoptera	Tineidae	1	Hymenoptera	Formicidae	343
Lepidoptera	Tortricidae	3	Hymenoptera	Ichneumonidae	1
Orthoptera	Acrididae	9	Hymenoptera	Pompilidae	1
Orthoptera	Gryllidae	5	Hymenoptera	Sphecidae	1
Orthoptera	Gryllotalpidae	3	Hymenoptera	Vespidae	1
Orthoptera	Tetrigidae	1	Lepidoptera	Bombycidae	1
Zygentoma	Lepismatidae	1	Lepidoptera	Crambidae	1
			Lepidoptera	Sphingidae	1
			Lepidoptera	Tineidae	1
			Lepidoptera	Tortricidae	1
			Orthoptera	Gryllidae	15
			Orthoptera	Tetrigidae	1
Total Abundance		**463**			**531**

Based on calculated Bray-Curtis dissimilarities of the three most abundant orders, Coleopteran communities appeared to differ considerably (Table 3-13). The dissimilarity reflects the differences noted above including the higher counts of Chrysomelidae in the FMNR treatment.

Table 3-13. Mean Bray-Curtis dissimilarity and SD sampled from four farms of the three most prominent insect orders.

Order	Mean Bray-Curtis dissimilarity	SD bray-Curtis dissimilarity
Coleoptera	0.755197	0.087264
Diptera	0.509848	0.172281
Hymenoptera	0.200609	0.109013

BAU and FMNR treatments appeared to have similar effective diversity at all tested levels of q. This suggests similar diversity between treatments (Figure 3-16). Finally, there were no discernable trends between farms or treatments of insect family richness (Figure 3-17).

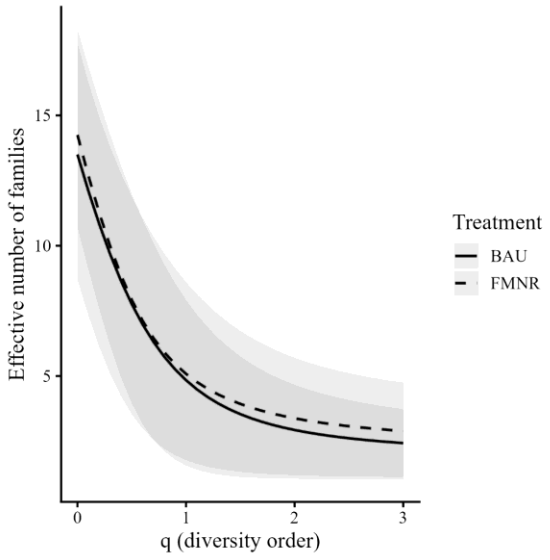


Figure 3-16. Diversity profiles as a function of q for the BAU (solid line) and FMNR (dashed line) treatment. The light gray band represents ± SD.

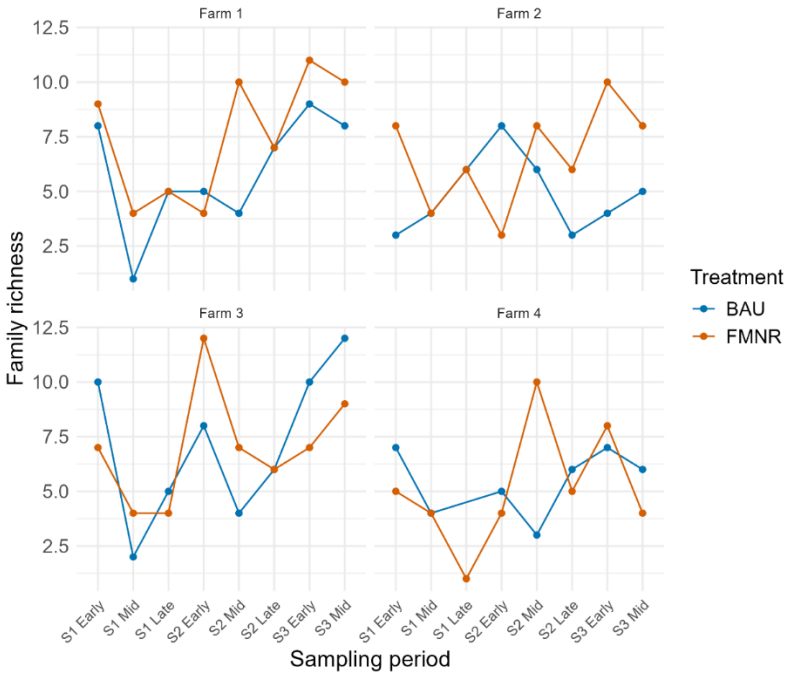


Figure 3-17. Family level richness is BAU and FMNR plots across four farms and eight sampling periods.

3.5 Conclusions

This study achieved the goal of describing the effects of FMNR interactions on biophysical parameters in Kenya. Across 25 farms in Kitui and Makueni County Kenya. We evaluated how FMNR influenced soil respiration, aggregate stability, hoe test scores, and water infiltration scores after two growing seasons. Across a subset of these farms, we evaluated how FMNR impacted insect communities, and how FMNR changed ground cover and biomass dynamics. Our results show that FMNR can have substantial impacts on these metrics even over two growing seasons. We noted higher soil respiration indicating higher microbial activity. Farmer led measurements found higher hoe test and water infiltration scores in FMNR plots compared to a BAU control indicating that these results were perceivable to farmers. The significant relationship between higher soil respiration scores and the farmer directed hoe test was observed, validating the perceptions of farmers. Results showed that FMNR plots had higher ground cover which has implications for reducing erosion and increasing water use efficiency. Herbaceous biomass samples where, at times in the FMNR plots, compared to the BAU plots. Our results

also showed farmer 'cashing in' on stored biomass in FMNR plots during periods of abnormally low rainfall. Collectively, the soil, biomass, and ground cover results suggest that FMNR can measurably benefit soil health and improve ecosystem resilience, even over two growing seasons.

FMNR increased the diversity of the insect community compared to a BAU control. Treatment differences that were driven mainly by ground crawling insects were captured in pitfall traps. It is yet to be determined how these differences in insect diversity will impact agricultural systems in the study area. Through observations on four farms, we observed that FMNR plots had higher rates of ground cover and herbaceous biomass compared to a BAU control. Insect observations on these four farms often demonstrated unclear trends between treatments. However, there were some indications that FMNR may be influencing Coleopteran communities. This should be explored further in future studies. Together these results demonstrate the potential of FMNR to create and restore resilient productive agroecosystems. While evidence for the impacts of FMNR in East Africa remain limited, this research contributes to addressing these gaps and clearly demonstrates that FMNR enhances ecological services.

CHAPTER 4. GENERAL DISCUSSION

5.1 Linking Biophysical benefits and adoption Constraints

Based on the findings in chapter 2, low income and low food security prohibited the adoption of FMNR. Two explanations were put forth to explain this. First, households with low incomes and low food may be unable or unwilling to make the upfront investments needed for FMNR implementation. Alternatively, FMNR may be increasing the incomes and food security of individuals who have already adopted the practice. The increase in biomass in season 2 of data collection and subsequent utilization in season 3 demonstrate the ability of FMNR to aid in resource partitioning during drought periods by increasing fodder availability during dry periods. This provides the opportunity to sell fodder at elevated prices or alternatively keep livestock fed, thus avoiding having to sell livestock out of desperation. Therefore, the evidence gathered in Chapter 3 supports the theory that the association between FMNR adoption and higher levels of income and food security may be a result of FMNR increasing incomes and food security instead of FMNR being a poor fit for poor and food insecure farmers. The challenge is therefore, how to overcome the hurdle of FMNR adoption and support farmers during the transition period – the time while they are waiting to capture the benefits of FMNR.

5.2 FMNR as an Argument for Land Sharing

Land sparing and land sharing refer to two competing ideologies around land use (Goulart et al. 2023). Land sparing argues that because some human managed ecosystems have poor abilities to support biodiversity even at low use intensities, land use policy should focus on intensifying production to reduce the land area needed to produce the same output. Land not needed for production, in theory, could then be set aside for parks and nature preserves. This approach has multiple flaws, including disregarding that increases in overall demand may be induced by more efficient production (i.e. Jevons paradox), the issues of forcibly removing people or restricting access to various parcels of land. This ignores the fact that modern neoliberal economics will not willingly limit production to ‘spare’ land.

Alternatively, land sharing argues for natural processes to coexist within human managed systems. This approach is practically synonymous with NbS, such as FMNR. The positive outcomes of FMNR observed in Chapter 2 highlight the ecological benefits that can be created in land sharing systems. Humans can create systems through practices like FMNR that mimic many components of natural systems. Land sharing approaches do not remove people from their lands and are compatible with a wide range of livelihoods and cultures, including smallholder farmers and pastoralists. However, these two ideologies are not mutually exclusive. The extirpation of large mammals from agroecosystems in East Africa speaks to the needs for preserves and spaces where human impact is minimal.

5.3 Defining Features of FMNR

During the oral defence of this thesis, a question was raised about "how do we distinguish or identify an FMNR system from other land-management or restoration systems?" Additionally, there was a desire for a "more concrete or operational definition of FMNR that would allow it to be identified consistently in practice." This is a communication challenge associated with these participatory, farmer-led practices, but it is also a demonstrated benefit in terms of ensuring that practices are well suited to farmers. I would propose the following key components as part of an operational definition for identifying FMNR: 1. Measured increases in tree densities because of natural regeneration, i.e. from root stock or soil seed bank. 2. Strategic management of these trees to promote more useful growth for farmers, i.e. height and an accessible understory.

5.4 Implications for NGOs

This research was conducted in close collaboration with the Canadian Foodgrains Bank and its African partners which provided a unique opportunity to situate these findings into the context of international development. Both the biophysical impacts (i.e. impacts to soil, ground cover, biomass and biodiversity) and adoption determinants have important implications for NGOs and development groups. Together the social and biophysical results help create a complete narrative for project proposals. The adoption determinants chapter helps to outline what groups to target, what barriers need to be addressed,

or what additional support is required to facilitate adoption of FMNR. Then the biophysical benefits outlined in chapter 3 provides an evidence base for the expected project impacts on people and the environment. Proof that FMNR has tangible benefits to people and the ecosystem strengthens project proposals and donor confidence.

Farmer education is a critical component of any future work and is an essential pathway to create positive ecological outcomes. For example, in chapter 2, a lack of training and information was identified to be a key constraint holding back NbS adoption. Subsequently, in chapter 3, the ability of FMNR to provide positive ecological outcomes was demonstrated. For these positive ecological outcomes to occur, organizations must have the capacity to train farmers on how the practice is implemented and what benefits they can expect.

One potential barrier to NbS adoption identified in the literature was that benefits took time. This may discourage farmers and lead to abandonment of NbS practices such as CA or FMNR. However, our results showed that farmers perceived soil benefits and water infiltration benefits from FMNR after just two growing seasons, as indicated by the hoe test and water infiltration score. This indicates that benefits to FMNR can be perceived rapidly by the farmer and demonstrates the role participatory measurements can play in helping farmers observe the impacts of their management practices. This information can then be incorporated into farmer training curriculums.

5.5 Contrasts and Synergies Between FMNR and CA

Labour is a key input in all smallholder agricultural systems. However, labour functions differently in CA and FMNR systems resulting in several key contrasts and potential synergies. While there is some debate as to the net effect of CA on labour requirements, there are several labour-intensive steps required for CA implementation. This process includes gathering and spreading mulch and, when herbicides are not used or mulch application is insufficient, manual weeding. These processes are relatively time sensitive and must occur on top of regular labour-intensive tasks of planting, growing, and harvesting

crops. Additionally, these labour demands are required each growing season. In contrast, the labour requirements of FMNR are extremely flexible, allowing the farmer to do these tasks when labour demand for other farm work is lower. While FMNR requires considerable labour to select, prune, clear unwanted shrubbery, and protect the area from livestock, this is largely a one-time investment requiring only occasional upkeep in the future.

There are further synergistic effects between CA and FMNR. For example, FMNR systems can provide a source of mulch for CA systems, which can could otherwise restrict proper adoption. Through communication with farmers directly, and literature reviewed in the chapters above, limited availably of mulch materials is a common constraint for CA adoption. Some farmers may use crop residues, but unless these residues are concentrated to a small area, they are insufficient to retain moisture and suppress weed growth. One farmer who was visited outside of the study area was attempting to use branches from a coniferous tree in a CA system due to a lack of other available sources of mulch material. This approach may reduce nutrient availability and reduce soil pH. If an FMNR system was present along side the CA system, the farmer could cut and carry the much material from the FMNR system and spread it around CA crops. This action would also redistribute the soil carbon and nutrients accumulated in the FMNR system. However, this combined system approach does not address the labour challenges associated with cut and carry, nor does it address the fact that famer may prioritize the use of mulch for livestock or for sale. CA can also be adopted within FMNR systems. This provides crops with partial shade, and nutrients concentrated around tress, especially where nitrogen-fixing reverse phenology *Fhaderbia albida* trees are used. Combining FMNR and CA could also ease the burden of mulching CA areas due to the proximity of mulch materials. CA systems could even be rotated through FMNR systems. Grasses would be tilled in, but trees would be allowed to persist. This shares a close similarity to swidden systems, traditionally used by many farming communities and would allow the farmer to harvest nutrients that have accumulated around trees.

FMNR provides opportunities for beekeeping through the diverse floral resources these systems provide. The bees may facilitate pollination of near by crops in CA systems. This was a one of the main reported benefits of FMNR at a site in Mandera County Kenya (pers comm., not discussed in this thesis). Crops in CA system can act as a food source for hives and potentially benefit from improved pollination.

5.6 Future Research

Future research should explore how perceived changes in farmer led soil health scores such as the hoe test, and water infiltration score, impact adoption. This would include evaluating how perceiving benefits from participatory tests impacts the intensity of adoption and rates of farmers discontinuing a practice. A similar study could also assess the long-term adoption outcomes of a group of farmers trained to use a variety of participatory assessment methods, such as those outlined in Entz et al. (2022), compared to a group of farmers who do not implement any participatory methods of evaluation.

Another related study idea could focus on how different kinds of information received by farmers impact probabilities of farmers adopting NbS such as CA or FMNR. In the available survey data utilized in chapter 2, there was no breakdown on what kinds of information farmers received. Understanding what forms of information was most effective in driving adoption would have immense practical use for local governments and NGOs. Furthermore, it would be valuable to parse how different types of reported benefits, including the benefits discussed in chapter 3, influence adoption decisions. For example, how does a farmer who is being told FMNR will increase their income impact adoption compared to a farmer being told this practice will improve local biodiversity? Or what is the relative importance of a farmer personally observing the benefits of a practice (e.g. through the hoe test) compared to being told what benefits they will eventually perceive.

5.6.1 Evaluating FMNR as a Mimic of Natural Systems

An interesting area for further research would be to examine whether FMNR can mimic some of the natural processes that were altered by human settlement. There are several ways FMNR may achieve

this. Through controlled grazing, FMNR mimics the intermittent grazing of migrating herds. Additionally, farmers practicing FMNR may open areas overgrown with undesirable thorny woody vegetation to allow for grasses to establish. This may mimic the actions of large grazing animals, elephants felling trees, and wildfires that reset areas to earlier stages of ecological succession.

Though there is a considerable body of literature on the ecology of these processes (which were not reviewed because they were outside the scope of this thesis), attempts to compare the impacts of large mammals and wildfires with those of FMNR. There may be opportunities to incorporate the findings of this ecological literature to further develop the principles and practices of FMNR. Or alternatively, practitioners can connect FMNR to these ecological practices to engage farmers and explain the broader benefits of FMNR. This framework of thinking– 'How well do the actions on my farm reflect natural systems?'–can be applied beyond FMNR as well.

5.6.2 Outlining The Need for a Controlled FMNR Trial

Assessments of FMNR in the previous two chapters have been either conducted through surveys or on-farm studies. While valuable, on farm studies can be messy, and it can be difficult or impossible find farms where FMNR and BAU are applied in similar ways, and under uniform conditions (i.e., the same soil type of similar topography). Furthermore, FMNR is seldom promoted in isolation, and farmers are encouraged to adapt the practice to suit their needs. This means that a precise prescribed definition of FMNR simply doesn't exist.

For these reasons, a long-term replicated controlled experiment would be helpful. Such an experiment could provide an interesting opportunity to strengthen and quantify the evidence base of FMNR. FMNR could either be assessed by individual components (i.e., isolate the effects trees on surrounding soil fertility, or the impacts of grass now growing on previously bare soil) or in combination. Currently, NGOs are the chief promoters of FMNR. These organizations lack the resources and operational mandates to conduct long-term monitoring of practices like FMNR in a controlled

environment. Partnering with local universities, institutions such as ICRAF and IITA or philanthropic foundations, may provide funding sources and support needed for a long-term trial.

The trial could be established as follows: a large relatively homogeneous section of land would be located with a landowner willing to participate with proper compensation. Management of this trial could be done in part by a group of trained local farmers who would have access to the products produced on the land and would receive additional compensation. This farmer group would collaborate with trial technicians and give advice on management practice timings that algin with farmers schedules and needs. This study could have the following treatments. A control treatment, where animals from surrounding farms are free to graze and collaborating farmers are encouraged to take wood products as needed. An FMNR treatment would be established on sections of land. These sections would be fenced off to control grazing, and vegetation would be pruned as per FMNR protocols. A second improved treatment, FMNR+ would be established. This would include enrichment planting of trees, planting of grasses, and water management structures, if relevant given the local topography. Baseline samples would be taken on all plots and removals of resources from improved plots (FMNR and FMNR+) would be carefully monitored. This would include weighing removals of wood, grasses, other forest products, and calculating grazing utilization. Detailed accounting of carbon stocks in these controlled environments would enable the use of soil health models such as DAYCENT, which would allow for predictions of future soil conditions based on the newly implemented practices. Assuming results manifest at a similar rate to what was observed in this thesis, after 1-2 years there should already be observable differences between treatments due to changes in herbaceous vegetation. An initial 7–10-year project timeline should allow for opportunities for significant tree regrowth to occur and changes to accumulate in the soil. The results of the projects can then be assessed, and the project can be extended if desired.

The findings of the study would quantify the impacts to carbon stocks, changes in productivity of the landscape, and changes to plant and animal diversity within the plots. This evidence would assist NGOs in sourcing funding for projects implementing FMNR in the future.

An emerging economic opportunity for farmers implementing NbS practices is the involvement in payment for ecosystem services programs. However, for this to be implemented, the ecosystem services produced by FMNR need to be clearly accounted for and cost-effective ways to measure these changes need to be development. In reviews of the literature, many impacts of FMNR were still poorly quantified. This hinders the implementation of payment schemes. While the biophysical data collected in this thesis does contribute to closing these gaps, more research is required specifically regarding benefits to biodiversity. The proposed long-term controlled research trial proposed above could make considerable progress in closing these remaining research gaps and enabling payment for ecosystem services programs on farms. A potential partner and funder for this long-term project is Natural State. They are an organization headquartered in Kenya that aims to facilitate the creation of financial mechanisms (i.e. payment for ecosystem services programs) to protect and preserve additional landscapes. The organization is in the process of developing sampling protocols and allometric equations to quantify the impacts of practices such as intensified grazing on biodiversity and carbon stocks. Their protocols could easily be applied to a long term FMNR trial.

5.7 FMNR and Farmer Agency

A phrase that was mentioned several times during meetings in Kenya was ‘dependency syndrome’ – the idea that people come to rely on outside assistance to make management decisions, community problem solving, resource provision may result in them being less capable of dealing with these challenges independently in the future. This can be a problem with top-down approaches to development, which prescribes solutions and often provide a subsidy or resources to implement the prescription. In contrast the inherent participatory nature of FMNR, and NbS more broadly, provide the farmer with tools to manage their natural resources more effectively and self-assess their priorities. Additionally, the participatory elements included in this research likely had unquantified benefits. One of these benefits is that it elevates the farmer from the role of ‘subject’ to ‘citizen scientist’. The process of evaluating the changes taking place on their farm helps them evaluate if the changes align with their personal needs.

Despite the benefits of participatory farmer led projects, there are instances where top-down approaches are necessary. For instance, there are cases that require decisive action or involve topics which farmers may have limited knowledge, such as vaccine campaigns, introduction of technologies like herbicides, or coordinating rapid responses to large scale disasters.

5.8 Conclusion and Contribution to Knowledge

This thesis evaluated how and why farmers adopted CA and FMNR, as well as quantified the impacts of FMNR in terms of soil health, soil cover, biomass stockpiling, and insect biodiversity. Chapter 2 addressed the ongoing need to better understand the contexts in which interventions promoted by development organizations are applicable and appealing to farmers. This is especially important in East African as the majority of studies on FMNR come from West Africa. This thesis contributed to knowledge by assessing what variables acted as promoters and barriers to the adoption of conservation agriculture practices including crop diversification, minimal soil disturbance, permanent soil cover, FMNR, and enrichment planting adoption in Kitui and Makueni County, Kenya. Results showed that poorer and food insecure households had decreased likelihood of adopting several NbS. This indicates that additional supports may need to be provided or that these practices have lower applicability to this demographic. Results also showed that exposure to environmental stressors, including drought, floods, biotic stressors (crop pests and diseases), as well as awareness of changing weather patterns, increased the likelihood of adopting NbS. This contribution of knowledge identifies that farmers are choosing NbS as a positive coping strategy. We predict that educating farmers on how climate change is expected to worsen these environmental stressors may help promote adoption. This study also identified training as one of the most important predictors of adoption, thereby stressing the importance of education. Given the low rates of training availability in these communities, the results of this study identified and quantified substantial potential to increase adoption through expanded access to information and training opportunities. These findings help identify the enabling environment required for successful NbS uptake and highlight which aspects of that environment need to be co-promoted by development projects for successful outcomes.

In Chapter 3 results showed that FMNR can have substantial impacts on soil health metrics, ground cover, and biomass dynamics, even over just two growing seasons. We noted higher soil respiration, indicating higher microbial activity. Farmer led measurements found higher hoe test and water infiltration scores in FMNR plots compared to a BAU control, indicating that these results were perceivable to farmers. The significant relationship between higher soil respiration scores and the farmer directed hoe test was observed, validating the perceptions of farmers. Results showed that FMNR plots had higher ground cover, which has implications for reducing erosion and increasing water use efficiency. Herbaceous biomass samples where at times higher in the FMNR plots compared to the BAU plots. Our results also showed farmers 'cashing in' on stored biomass in FMNR plots during periods of abnormally low rainfall. Collectively, the soil, biomass, and ground cover results suggest that FMNR can measurably benefit soil health and improve ecosystem resilience, even over two growing seasons.

To the authors knowledge, this study represents the first quantification of the impacts of FMNR on insect biodiversity and community dynamics. FMNR increased the diversity and richness of the insect community compared to a BAU control, these treatment differences were driven mainly by ground crawling insects captured in pitfall traps. It is yet to be determined how these differences in insect diversity will impact agricultural systems in the study area. As well, through observations on four farms, it was observed that FMNR plots had higher rates of ground cover and herbaceous biomass compared to a BAU control. There were also some indications that FMNR may be influencing Coleopteran communities. This should be explored further in future studies. Together these results demonstrate the potential of FMNR to create and restore resilient productive agroecosystems. While evidence for the impacts of FMNR in East Africa remain limited, this research contributes to addressing these gaps and clearly demonstrates that FMNR enhances ecological services.

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APPENDIX A - CHAPTER 2

Supplementary Figures

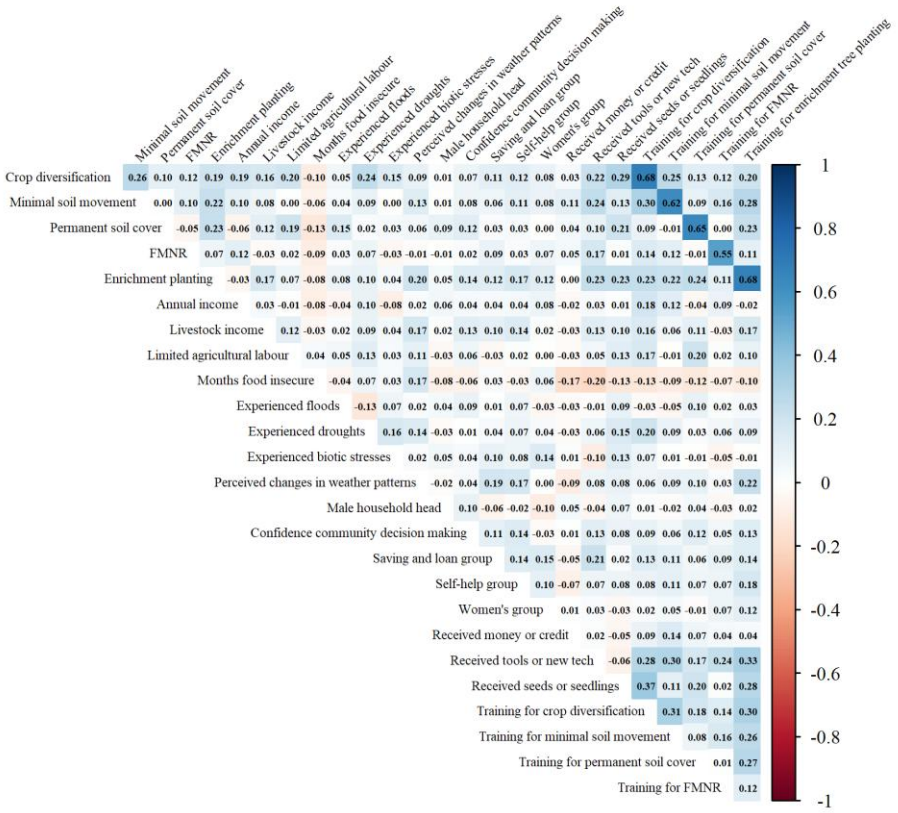


Figure A-1. Correlation matrix of logistic regression model variables including dependent variables. Darker colours represent stronger correlation coefficients, with blue indicating positive correlations and red indicating negative correlations.

Table A-1. Adjusted VIF values calculated from logistic regression model outputs.

Variable	Crop diversification	Minimal soil Disturbance	Permanent soil cover	FMNR	Enrichment planting
Annual income	1.086	1.094	1.093	1.165	1.094
Livestock income	1.032	1.048	1.046	1.068	1.032
Limited agricultural labour	1.024	1.042	1.049	1.084	1.05
Months food insecure	1.115	1.119	1.099	1.109	1.098
Experienced floods	1.076	1.102	1.08	1.084	1.056
Experienced droughts	1.066	1.117	1.169	1.087	1.157
Experienced biotic stresses	1.251	1.154	1.126	1.263	1.188
Perceived changes in weather patterns	1.127	1.141	1.14	1.191	1.1
Male household head	1.042	1.053	1.041	1.106	1.04
Confidence community decision making	1.052	1.042	1.034	1.082	1.038
Saving + loan group	1.119	1.123	1.122	1.095	1.127
Self-help group	1.047	1.051	1.06	1.155	1.054
Women's group	1.099	1.081	1.11	1.141	1.083
Received money or credit	1.088	1.076	1.04	1.086	1.058
Received tools or new technology	1.123	1.123	1.152	1.238	1.113
Received seeds or seedlings	1.137	1.132	1.119	1.081	1.136
Training for crop diversification	1.151	NA	NA	NA	NA
Training for minimal soil movement	NA	1.084	NA	NA	NA
Training for permanent soil cover	NA	NA	1.084	NA	NA
Training for FMNR	NA	NA	NA	1.291	NA
Training for enrichment tree planting	NA	NA	NA	NA	1.103
Partner	1.237	1.244	1.246	1.281	1.228

Table A-2. Results of five logistic regression models. Coefficient estimates are presented, followed by indication of significance (* < 0.05, ** < 0.01, *** < 0.001. '.' Indicates 0.1), and standard error in parentheses.

	Crop diversification	**Minimal soil disturbance**	**Permanent soil cover**	**FMNR**	**Enrichment planting**
Annual income	0.202* (0.080)	0.007 (0.069)	−0.120 (0.076)	0.740*** (0.218)	−0.065 (0.072)
Livestock income	0.244 (0.156)	0.067 (0.157)	0.427* (0.189)	−0.312 (0.387)	0.275. (0.149)
Limited agricultural labour	0.724** (0.231)	−0.265 (0.236)	0.657** (0.251)	0.593 (0.511)	−0.086 (0.227)
Months food insecure	−0.009 (0.033)	−0.001 (0.033)	−0.093* (0.040)	−0.186* (0.095)	−0.046 (0.030)
Experienced floods	0.913*** (0.211)	0.838*** (0.215)	0.744** (0.236)	−0.016 (0.511)	0.428* (0.209)
Experienced droughts	0.654* (0.262)	0.286 (0.247)	0.347 (0.295)	1.857 (1.180)	0.558* (0.229)
Experienced biotic stresses	1.138*** (0.199)	0.047 (0.188)	0.094 (0.212)	−0.041 (0.488)	−0.192 (0.184)
Perceived changes in weather patterns	0.177 (0.170)	0.452** (0.171)	0.187 (0.206)	−0.491 (0.430)	0.075 (0.159)
Male household head	0.086 (0.180)	0.269 (0.181)	0.497* (0.236)	0.425 (0.461)	0.349* (0.171)
Confidence community decision making	−0.069 (0.189)	0.333. (0.191)	0.385 (0.246)	−0.689 (0.487)	0.223 (0.178)
Saving + loan group	−0.014 (0.171)	−0.467** (0.170)	0.310 (0.204)	0.536 (0.400)	−0.343* (0.164)
Self-help group	0.164 (0.160)	0.053 (0.158)	−0.095 (0.193)	0.026 (0.426)	0.279. (0.152)
Women's group	0.617** (0.208)	0.488* (0.209)	0.303 (0.258)	0.406 (0.485)	0.385. (0.209)
Received money or credit	−0.361 (0.305)	0.598* (0.273)	0.108 (0.310)	0.994. (0.550)	0.127 (0.294)
Received tools or new tech	0.449. (0.231)	0.535** (0.206)	0.237 (0.258)	0.001 (0.455)	0.023 (0.227)
Received seeds or seedlings	0.195 (0.184)	0.542** (0.176)	0.536** (0.206)	0.014 (0.400)	0.656*** (0.185)
Training for crop diversification	3.012*** (0.185)				
Training for minimal soil disturbance		2.802*** (0.165)			
Training for permanent soil cover			3.480*** (0.208)		
Training for FMNR				4.431*** (0.478)	
Training for enrichment tree planting					3.211*** (0.170)
NCCK	0.852** (0.267)	0.094 (0.270)	0.701* (0.311)	−1.430* (0.650)	−1.705*** (0.269)
UDO	0.815** (0.276)	1.002*** (0.271)	−0.982** (0.351)	−0.951 (0.623)	−0.414 (0.259)
Fadhili Trust	−0.621* (0.259)	0.067 (0.268)	1.050*** (0.310)	−2.478** (0.842)	−0.535* (0.235)
N	1529	1529	1529	1529	1529
AIC	1189.24	1218.98	896.58	289.57	1284.57
McFadden R^2	0.447	0.358	0.424	0.462	0.413

Table A-3. Average marginal effects (AME) for binary model variables shown followed by 95% confidence intervals and significance. Significance vales were obtained directly from model outputs. (* < 0.05, ** < 0.01, *** < 0.001. '.' Indicates 0.1). Prob0 indicates the model estimated probability under the counterfactual scenario in which all survey participants have a zero for a given predictor. Prob1 indicates the model estimated probability under the counterfactual scenario in which all survey participants have a one for a given predictor.

Variable	Crop diversification			Minimal soil disturbance			Permanent soil cover			FMNR			Enrichment planting		
	AME	pro b0	pro b1	AME	pro b0	pro b1	AME	pro b0	pro b1	AME	pro b0	pro b1	AME	pro b0	pro b1
Livestock income	0.028 [-0.009, 0.064]	0.402	0.431	0.008 [-0.029, 0.044]	0.283	0.291	0.035 [0.005, 0.068]*	0.172	0.207	-0.006 [-0.027, 0.010]	0.038	0.031	0.035 [-0.001, 0.076].	0.498	0.533
Limited agricultural labour	0.089 [0.029, 0.155]**	0.405	0.494	-0.030 [-0.080, 0.019]	0.291	0.261	0.059 [0.014, 0.111]**	0.18	0.239	0.013 [-0.009, 0.052]	0.033	0.046	-0.011 [-0.065, 0.042]	0.515	0.505
Experienced floods	0.110 [0.059, 0.163]***	0.398	0.509	0.105 [0.052, 0.162]***	0.272	0.377	0.066 [0.027, 0.118]**	0.177	0.244	-0.000 [-0.020, 0.030]	0.035	0.034	0.055 [0.003, 0.107]*	0.506	0.561
Experienced droughts	0.074 [0.016, 0.138]*	0.351	0.425	0.033 [-0.022, 0.084]	0.259	0.292	0.027 [-0.022, 0.068]	0.167	0.194	0.026 [-0.022, 0.045]	0.011	0.037	0.070 [0.021, 0.126]*	0.456	0.526
Experienced biotic stresses	0.137 [0.092, 0.190]***	0.374	0.511	0.006 [-0.035, 0.053]	0.285	0.291	0.008 [-0.026, 0.042]	0.186	0.194	-0.001 [-0.025, 0.023]	0.035	0.034	-0.024 [-0.069, 0.018]	0.522	0.498
Perceived changes in weather patterns	0.020 [-0.017, 0.058]	0.406	0.426	0.054 [0.014, 0.094]**	0.26	0.314	0.015 [-0.019, 0.050]	0.182	0.197	-0.010 [-0.031, 0.006]	0.04	0.03	0.010 [-0.031, 0.053]	0.51	0.519
Male household head	0.010 [-0.029, 0.049]	0.409	0.419	0.031 [-0.012, 0.071]	0.264	0.295	0.038 [0.002, 0.071]*	0.16	0.198	0.008 [-0.013, 0.026]	0.029	0.037	0.044 [-0.001, 0.088]*	0.482	0.526
Confidence community decision making	-0.008 [-0.050, 0.034]	0.422	0.414	0.038 [-0.006, 0.082].	0.257	0.296	0.030 [-0.010, 0.065]	0.165	0.195	-0.015 [-0.048, 0.005]	0.048	0.032	0.028 [-0.017, 0.074]	0.493	0.521
Saving + loan group	-0.002 [-0.041, 0.036]	0.417	0.415	-0.054 [-0.089, -0.017]**	0.311	0.257	0.025 [-0.006, 0.059]	0.179	0.204	0.011 [-0.005, 0.035]	0.029	0.04	-0.043 [-0.085, -0.002]*	0.532	0.489
Self-help group	0.019 [-0.017, 0.054]	0.405	0.424	0.006 [-0.030, 0.044]	0.284	0.29	-0.008 [-0.039, 0.025]	0.193	0.186	0.001 [-0.018, 0.018]	0.034	0.035	0.036 [-0.001, 0.074].	0.495	0.531
Women's group	0.073 [0.023, 0.123]**	0.402	0.476	0.060 [0.008, 0.116]*	0.277	0.337	0.025 [-0.014, 0.073]	0.185	0.21	0.009 [-0.012, 0.039]	0.033	0.042	0.050 [-0.003, 0.103].	0.506	0.555
Received money or credit	-0.040 [-0.107, 0.029]	0.419	0.379	0.076 [0.009, 0.154]*	0.28	0.356	0.009 [-0.035, 0.069]	0.188	0.197	0.025 [-0.002, 0.077].	0.032	0.057	0.016 [-0.057, 0.093]	0.513	0.529
Received tools or new tech	0.054 [-0.001, 0.112].	0.407	0.461	0.068 [0.015, 0.122]**	0.274	0.341	0.020 [-0.019, 0.067]	0.185	0.205	0.000 [-0.019, 0.024]	0.035	0.035	0.003 [-0.048, 0.061]	0.514	0.517
Received seeds or seedlings	0.023 [-0.021, 0.069]	0.409	0.432	0.066 [0.024, 0.111]**	0.265	0.331	0.045 [0.009, 0.086]**	0.173	0.218	0.000 [-0.017, 0.019]	0.035	0.035	0.087 [0.039, 0.139]***	0.491	0.578
Received training	0.539 [0.469, 0.594]***	0.218	0.757	0.526 [0.457, 0.574]***	0.135	0.661	0.558 [0.484, 0.611]***	0.083	0.641	0.356 [0.243, 0.490]***	0.014	0.37	0.601 [0.543, 0.642]***	0.257	0.858

Table A-4. Predicted probabilities of adoption for selected annual household incomes. Predicted probabilities are followed by lower and upper 95% confidence intervals (bootstrapped, n=500) in square brackets.

Annual income (KES)	Crop diversification	Minimal soil disturbance	Permanent soil cover	FMNR	Enrichment planting
10,000	0.379 [0.343, 0.413]	0.286 [0.251, 0.316]	0.204 [0.181, 0.230]	0.013 [0.006, 0.023]	0.527 [0.487, 0.564]
50,000	0.416 [0.393, 0.442]	0.287 [0.264, 0.310]	0.188 [0.172, 0.207]	0.030 [0.021, 0.038]	0.514 [0.489, 0.538]
100,000	0.433 [0.407, 0.461]	0.288 [0.262, 0.314]	0.181 [0.163, 0.203]	0.041 [0.030, 0.053]	0.508 [0.480, 0.537]
200,000	0.450 [0.414, 0.488]	0.288 [0.258, 0.320]	0.175 [0.154, 0.199]	0.056 [0.038, 0.078]	0.502 [0.467, 0.536]
300,000	0.460 [0.420, 0.504]	0.289 [0.255, 0.324]	0.171 [0.149, 0.197]	0.067 [0.043, 0.102]	0.499 [0.459, 0.537]
400,000	0.467 [0.424, 0.516]	0.289 [0.252, 0.327]	0.169 [0.144, 0.197]	0.077 [0.047, 0.120]	0.497 [0.453, 0.538]
500,000	0.473 [0.427, 0.526]	0.289 [0.250, 0.329]	0.167 [0.141, 0.197]	0.085 [0.049, 0.137]	0.495 [0.448, 0.539]

Table A-5. Predicted probabilities of adoption for selected months of food insecurity. Predicted probabilities are followed by lower and upper 95% confidence intervals (bootstrapped, n=500) in square brackets.

Months food insecure	Crop diversification	Minimal soil disturbance	Permanent soil cover	FMNR	Enrichment planting
0	0.420	0.288	0.223	0.051	0.541
	[0.382, 0.463]	[0.250, 0.325]	[0.186, 0.263]	[0.031, 0.083]	[0.497, 0.584]
3	0.417	0.287	0.198	0.037	0.523
	[0.390, 0.444]	[0.260, 0.314]	[0.176, 0.218]	[0.027, 0.049]	[0.496, 0.550]
6	0.414	0.287	0.175	0.026	0.506
	[0.387, 0.440]	[0.261, 0.311]	[0.153, 0.196]	[0.015, 0.037]	[0.481, 0.530]
9	0.411	0.286	0.155	0.018	0.489
	[0.373, 0.452]	[0.246, 0.327]	[0.126, 0.188]	[0.006, 0.033]	[0.450, 0.526]
12	0.409	0.286	0.136	0.013	0.472
	[0.355, 0.464]	[0.233, 0.347]	[0.100, 0.181]	[0.002, 0.033]	[0.416, 0.527]

APPENDIX B – CHAPTER 3

Supplementary Figures

Table B-1. Reference table for farmer-based assessments: Hoe test, water infiltration. Adapted from Entz et al., (2022).

Assessment Category	Score 1	Score 2	Score 3	Score 4	Score 5
Hoe Test	Soil is hard, very difficult to hoe to a proper depth (evidence of a hard pan/restrictive layer), soil comes up as large chunks.	Soil is moderately hard, able to hoe to proper depth, soil comes up as large chunks that are difficult to break up.	Soil is firm, able to hoe to proper depth, some chunks of soil, chunks break up under moderate pressure.	Soil is relatively easy to hoe, some chunks of soil may be observed, chunks break up with ease.	Soil is soft and easy to hoe, no chunks of soil are observed, soil has good crumb structure.
Water Infiltration	Absorbs water very slowly, lots of runoff and erosion, ponding happens after light rains.	Absorbs water slowly, some runoff and erosion, ponding happens after moderate rains.	Absorbs water slowly, some runoff and erosion, ponding happens after heavy rains.	Absorbs water quickly, very little runoff or erosion, ponding happens only after heavy rains.	Rainfall soaks in quickly, no runoff or erosion, water does not pond.

Table B-2. Mean herbaceous biomass (kg ha^{-1}) and SD

Sample	Treatment	Mean biomass	SD
Mid S1	BAU	574.1	297.6
Mid S1	FMNR	693.8	311.2
Late S1	BAU	567.9	61.4
Late S1	FMNR	737.6	331.0
Mid S2	BAU	356.7	234.6
Mid S2	FMNR	577.2	281.0
Late S2	BAU	503.4	62.0
Late S2	FMNR	1009.6	409.3
Mid S3	BAU	627.0	241.4
Mid S3	FMNR	518.1	168.7

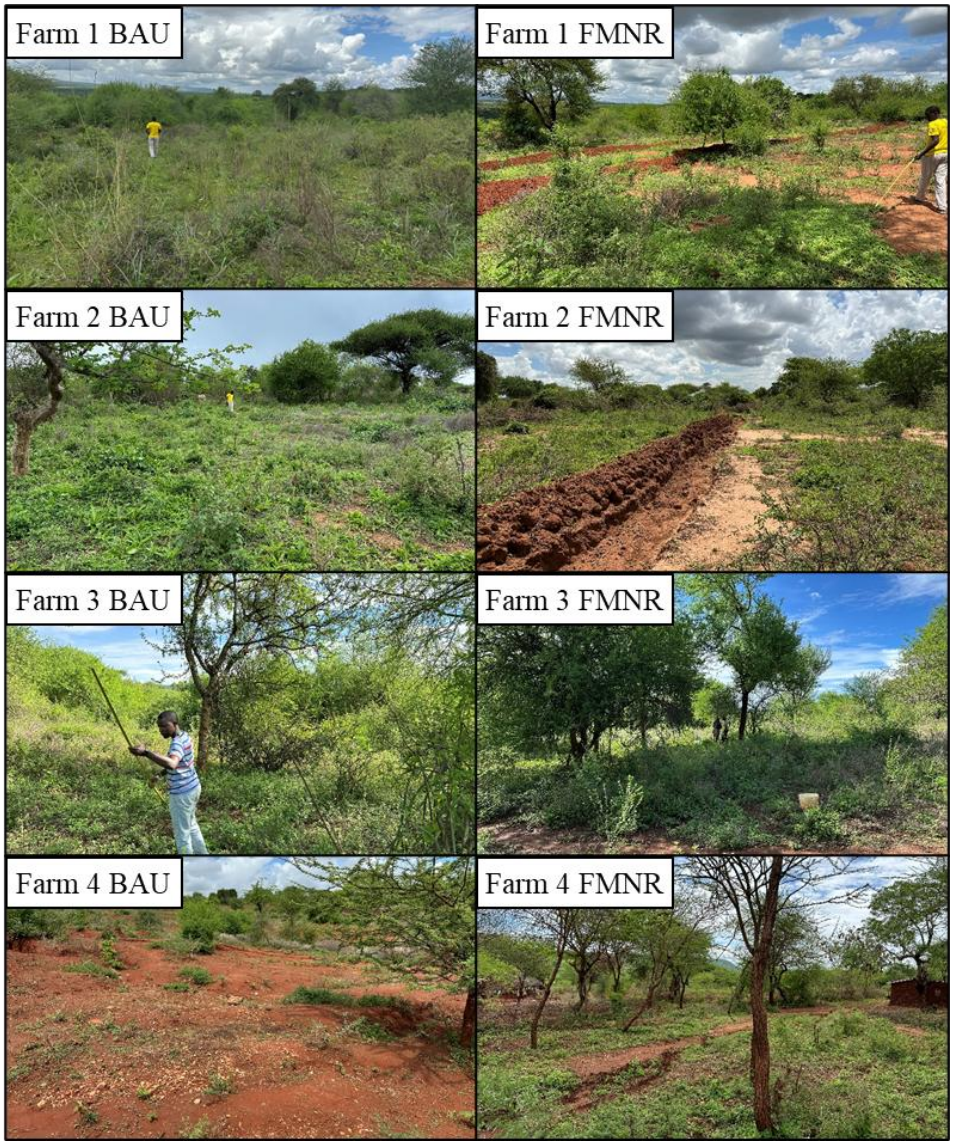


Figure B-1. Photographs taken in November, 2024 of sampling areas included in the 'focal farm' dataset.

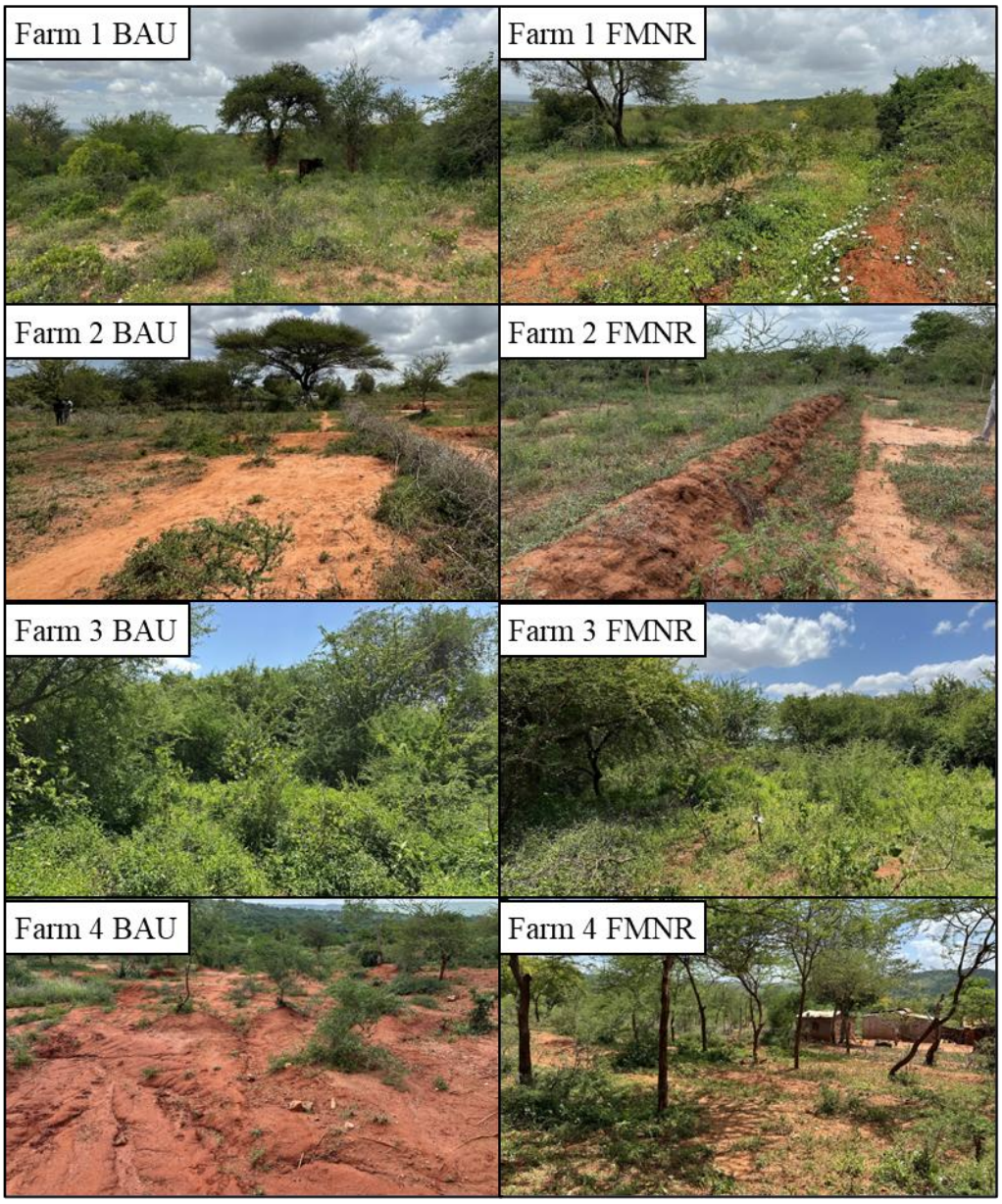


Figure B-2. Photographs taken in January, 2026 of sampling areas included in the 'focal farm' dataset.

Table B-3. Reported soil textures from farms included in the soil dataset.

Soil texture	Number of plots
Sandy Loam	12
Clay Loam	10
Sandy Clay Loam	8
Loam	6
Loamy Sand	4
Sandy clay	4
Sandy clay loam	2
Silty clay	2
Silty clay loam	2

Enumerator Training and Data Collection Manual

This appendix contains the full enumerator training and data collection manual used during fieldwork in Kenya. It includes reference to treatments and data collection that was dropped from the final thesis

List of abbreviations:

FMNR: farmer managed natural regeneration

CA: conservation agriculture

CG: continuously grazed – land used for grazing that livestock have continuous access to.

CON: conventional farming- business as usual cropping practices the farmer uses.

Overview of measurements

Early season stage

1. Bee bowls
2. Pitfall traps

Mid season stage

1. Bee bowls
2. Pitfall traps
3. Ground cover
4. Herbaceous biomass
5. Residue biomass

Late season stage

1. Bee bowls
2. Pitfall traps
3. Ground cover
4. Herbaceous biomass
5. Residue biomass

General sampling considerations

Treatments on a given farm should be sampled on the same day. A particular measurement, e.g., bee bowls, should be completed on all farms as closely together in time as possible. Take general pictures of the fields when they are visited. Send these to Andrew. Make a note of when each measurement occurs. Enter this on a provided Excel sheet.

A note on periods between collection time:

Most materials can be left in the field between collection times if acceptable with the farmer. For the bee bowls, posts can be left in the ground with platforms still attached. The coloured cups should be taken out of the sun. For the pitfall traps, containers can be left in the ground to save the effort of having to dig the holes additional times. Consider using the lids that came with the containers to keep dirt and animals out of the containers between sampling times.

Bee bowls

Four bee bowl stations will be established per field. Bee bowl stations will be constructed as per Figure 2 below. Stations will be placed randomly within the field, placed away from field borders as per Figure 3. Traps will be set out three times: at vegetative growth stage, crop flowering and post-harvest.

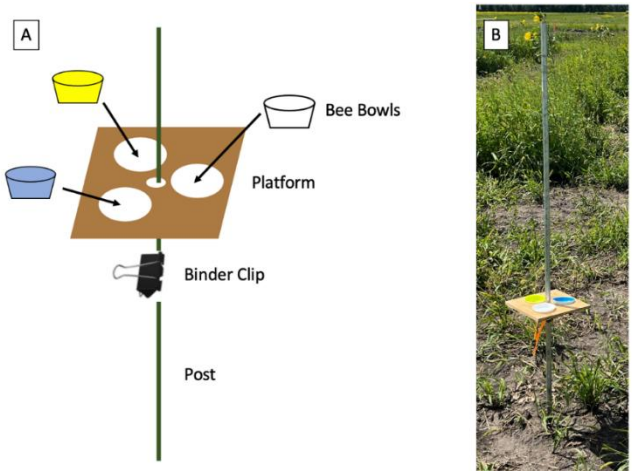


Figure 2. Example of a setup bee bowl station. (A) diagram of bee bowl setup. (B) Picture of bee bowls set up in a field. Figure obtained from Victoria Smelko).

Materials required:

For each plot:

1. 4x polls, at least 1m tall, will need to be high enough to sit at the height of the crop
2. 4x clips to hold platforms
3. 4x platforms to hold cups
4. 4 white, 4 yellow and 4 blue cups

General materials:

1. Tweezers/forceps
2. strainer
3. Soapy water - 4L of water to 1 teaspoon (5ml) of liquid dish soap, if possible unscented. Please note the type of soap used.
4. Surgical spirits/Ethanol/Isopropyl alcohol. At least 70%.
5. Plastic bags (provided)
6. Labels (provided)

Set up instructions:

1. Place the pole in the ground at random locations away from field margins (Figure 3).
    a. If you can see the bee bowls, so can the bees. Place bee bowls in areas that are clear of obstructions.
2. Secure adjustable platform onto post at average crop height. Place a large binder clip under the platform to secure it to the post (Figure 2).
3. Place one of each colour of bowls (blue, yellow, and white) on the platform (Figure 2).

4. Fill each bowl 3/4 full of soapy mixture (4L of water to 1 teaspoon (5ml) of liquid dish soap, if possible unscented).

Collection instructions:

1. Collect each bee bowl sample after 48 hours. Collect samples in the same order they were set up. For example, if on one day samples were set up in the order of Farm #1, #2, #3, #4 then they should be collected in the same order.
    a. Separate insects from soapy liquid by pouring the cups into the strainer.
    b. Place insects into labeled plastic bags. Gently pick up insects by the base of the wing or leg. For larger insects gently grasping them by the thorax (middle part of the body) is also appropriate.
    c. Any damaged, dried, or empty traps will be noted, it should be recorded if no specimens were caught.
    d. Make note of the general weather conditions that have occurred over the last 48 hours. Record if it's been mostly sunny, a mix of sun and cloud, mostly cloudy, or mostly rainy. Use the same Excel sheet for the entering measurement collection dates to enter general weather observations.
2. Once the plastic bags contain all the insects from all three cups from one bee bowl station, pour ethanol/surgical spirits into the bags to preserve the samples (enough liquid to cover the insects).
3. Double check to ensure correct label is on the plastic bag.
4. Close the plastic bags. Leave a small amount of air at the top of the closed bag, too much air could allow the plastic bags to leak. Place sample bags in a box upright. Samples placed upside down or laying down may leak.
5. Bee species and count should be identified as soon as possible after collection. Bees can be frozen for future identification as well.
6. Samples will be sent to SEKU and identified to the family taxonomic level.

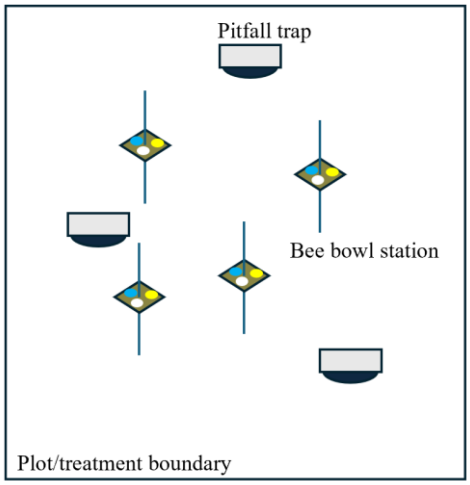


Figure 3. Diagram of pitfall traps and bee bowl stations set up in a field.

Pitfall traps

Used to capture ground-based insects/arthropods, including beetles and spiders. Three traps will be established per plot. Select three semi-random locations within the field. At each farm, try to select sites

in the plot with similar amounts of residue even between treatments. This ensures that insect mobility is not a confounding factor. Traps consist of a cup dug into the ground to lie flush with the soil (Figure 4). Traps will be set out three times per growing season: at the vegetative stage, crop flowering stage, and post-harvest stage. They will be set out for 48 hours at a time.

Materials required:

General materials

1. A garden spade or a small shovel to dig a hole that fits the pitfall trap, so it is flush with the ground.
2. A container to strain the liquid into.
3. Tweezers/forceps
4. Fine meshed strainer

Per one pitfall trap station (Figure 4)

1. One large plastic cup
2. Exclusionary grid: 15 x 15 cm square of chicken wire
3. Rain cover + nails: 15 x 15 cm: corrugated plastic, four ~8 cm metal nails
4. Soapy water - 4L of water to 1 teaspoon (5ml) of liquid dish soap, if possible unscented. Please note the type of soap used.
5. Plastic bags (provided)
6. Labels (provided)

Set up instructions:

1. Locate the area where you want to set up the pitfall trap to collect insects. This location should be randomly selected through the field. At each farm, select areas with similar amounts of residue, even between treatments.
2. Dig a hole large enough for the container to sit flush to the ground and place container in hole, push dirt around the container so that there are no gaps around the cup.
3. Add soap and water mixture to ensure the pitfall trap is around 1/3 full of liquid (without the liquid, the insects will crawl out!).
    a. Do not worry if the liquid is muddy, it is still effective.
4. Ensure the pitfall is flush with the ground (Figure 4).
    a. If not, adjust pitfall trap.
        i. Assess how to make the pitfall trap as flush to the ground as possible. You may need to dig the pitfall trap hole slightly deeper or raise it up with more soil under the trap.
        ii. Ensure there are no small holes in the soil around the edge of the pitfall trap, as smaller ground beetles and animals make holes to get around the trap.
5. Put the exclusionary grid into place as close to the ground as possible so it covers the whole trap opening (this keeps small animals out of the trap)
6. Put the rain cover in place by pushing the nails into the ground (use your own judgement as to the depth the nails go into the ground you want to make sure there is at least 4 cm of space between the rain cover and the ground to allow for larger ground beetles to get into the trap easily).
    a. The nails should be placed within the corners of the exclusionary grid to ensure the grid stays in place.
        i. When doing this, the exclusionary grid is as flat on the ground as possible.
    b. To get the rain cover and exclusionary grid to stay in place, angle the nails slightly on the ground.

7. Repeat the process for all pitfall traps.

Collection instructions:

1. After 48 hours, collect insects.
    a. Pour the soapy water containing the insects over a strainer to separate out the insects. Place an extra cup underneath to catch the water. Use this water to rinse dirt off the insects if they are muddy.
    b. Place insects into labelled plastic bags. Gently pick up insects by the base of the wing or leg. For larger insects gently grasping them by the thorax (middle part of the body) is also appropriate.
    c. Any damaged, dried, or empty traps will be noted, it should be recorded if no specimens were caught.
2. Once the plastic bags contain all the insects from all three cups from one bee bowl station, pour ethanol/surgical spirits into the bags to preserve the samples (enough liquid to cover the insects).
3. Double-check to ensure the correct label is on the plastic bag.
4. Close the plastic bags. Leave a small amount of air at the top of the closed bag, too much air could allow the plastic bags to leak. Place sample bags in a box upright. Samples placed upside down or laying down may leak.
5. If carefully removed the soil should hold its shape allowing for the container to be reinserted into the hole after insects have been collected. Place the screw on lid that came with the containers on to the container to keep soil water and animals from getting in between sample collection. Trap materials can be left like that in the field until next collection time.

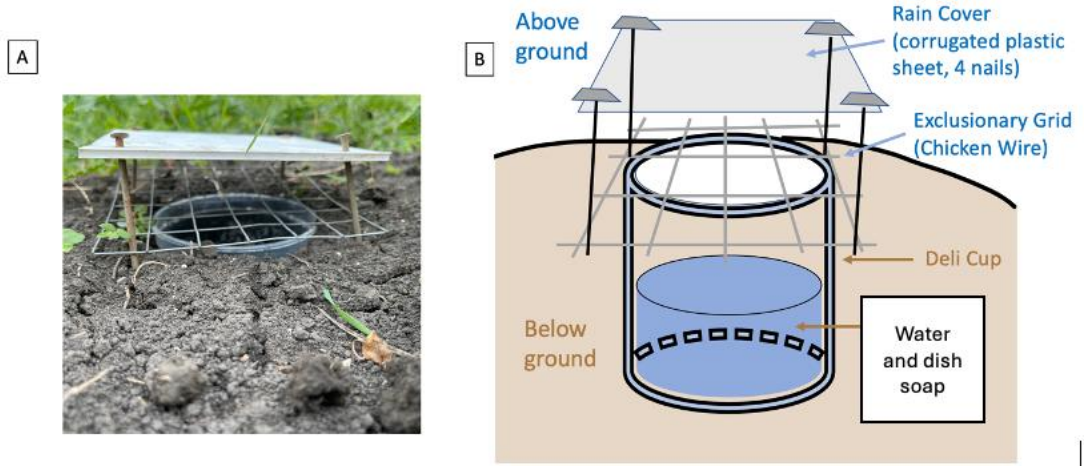


Figure 4. (A) Pitfall trap set out in a field. (B) Diagram of pitfall trap components. Figure obtained from Victoria Smelko).

Ground cover

Randomly select four locations in the field using a Z-shaped sampling pattern. Extend a tape measure to 5m and place it on the ground in a random location. Looking straight down, at every 10cm mark, count if there is living/plant residue obstructing the soil. Only consider material that is within 10cm of the soil surface. For example, if a maize leaf is 50cm above the soil, it will not be counted as ground cover. This will give a value for ground cover out of 50. Multiply this value by 2 to obtain percent ground cover. Lay the tape measure diagonally across rows if rows are visible in CA and CON fields. Avoid placing parallel

or perpendicular to the rows. In FMNR and CG, the tape can be measured at random orientation. Collect samples at a similar time to bee bowls and pitfall traps. Take measurements at three times. 1. After mulch application at the vegetative crop stage (same time as bee bowls/pitfall trap sampling) 2. At crop flowering 3. Post-harvest.

Herbaceous biomass (FMNR and CG)

Collect samples twice over the growing season. Once at the crop flowering stage (flowering stage of the legume if in an intercrop of maize and a legume). A second time is during the post-harvest measurement period. It is impossible to get every last bit of plant material. Rather than trying to achieve the impossible, try to be consistent with the effort on each sample area so that samples are comparable.

Defining Herbaceous vs. Woody plants:

Woody plants: hard, thick, sturdy stems that persist for multiple years. We **do not** want to collect these.

Herbaceous plants: flexible, usually green stems that die back at the end of the growing season.

1. Randomly select 4 locations in the field roughly in a Z shape. Place a 0.25 m^2 quadrat or alternatively mark an area of 0.5m by 0.5m using stakes and string.
2. Using shears or a sickle, collect herbaceous (non-woody) plant material (e.g. grasses, weeds, other small plants), including living material and non-woody dead plant material (excluding living trees and shrubs). Cut plant material to the soil surface. Take care not to get any dirt in the sample. See the following cases when a plant material should be included or excluded:
    a. Leaves on a woody shrub: EXCLUDE
    b. Loose branch: EXCLUDE
    c. Plant with a hard stem that has died back for the year: INCLUDE
3. If a plant lies on the edge of the sampling area, include it if the majority of the base of the plant falls within the sampling area. In this case, **include** the entire plant. If most of the plant base falls outside the sampling area, **exclude** it entirely. If lose plant residue lies on the border, cut and take the piece that lies inside the sampling area.
4. Once samples are collected, leave the tops of the bags open and leave them in the sun to dry until they appear completely dry (time depends on weather conditions, likely 2-3 days. Ensure they don't get rained on.
5. Samples once air-dried, can be stored for a considerable time and then taken to SEKU when convenient. Samples will be sent to SEKU for analysis.
6. Samples will be oven-dried at 75 degrees C for 24 hours to remove residual moisture and then weighed immediately.

Residue/mulch biomass (CA, CON)

Collect samples twice in the growing season. Ask farmers when they apply the mulch on CA fields and make a note of this, record data in the same Excel sheet as measurement dates. If the farmer does not apply mulch and just uses existing crop residue, make a note of this instead of entering a date. The first residue/mulch sample will occur at the flowering sampling time. The second sampling will occur during the post-harvest sampling time. It is impossible to get every last bit of plant material. Rather than trying to achieve the impossible, try to be consistent with the effort on each sample area so that samples are comparable.

Materials required:

1. 0.25 m^2 quadrat, or string and stakes, to mark a 0.5 m x 0.5 m sampling area.
2. Large paper sample bags, reference bags I left as an example to an appropriate sample bag. Smaller sizes may work depending on the quantity of residue expected.
3. Clippers/garden sheers,
4. Labels

Procedure to collect samples:

1. Randomly select four locations in the field roughly in a Z shape across the treatment area.
2. Place a 0.25 m^2 quadrat or mark an area of 0.5 m by 0.5 m using stakes and string.
3. Within the quadrat, collect all above-ground dead plant material on the soil surface.
    a. Use the shears/clippers to cut along the edges of the sampling area to cut any residue pieces that lay both inside and outside of the sampling area.
    b. For dead plant material still rooted in the soil, use shears or a small sickle to cut the residue as close to the surface.
4. Not every tiny fragment of plant material needs to be collected. Collect all major leaves, stems, husks etc.
    a. Take a picture before and after taking the first sample in each treatment. You do not need to take photos of this sampling on every farm. This is both for my information and can be used as a reference to help ensure residue is collected consistently.
    b. Take care not to include any soil in the sample. Samples can initially be air-dried and then taken to SEKU when convenient.
5. Samples will be sent to SEKU for analysis. Samples will be oven-dried at 75 degrees C for 24 hours (or until completely dry) and then weighed immediately.