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Linking On-farm Land Restoration and Livelihoods in the Drylands of Eastern Kenya

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Thesis for the degree of Doctor of Philosophy in Agriculture

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Summary

A pervasive challenge to ending hunger and reducing poverty is that farming practices known to sustainably increase production and reduce and reverse land degradation processes are not widely adopted by smallholder farmers. Current approaches to development-focused agricultural research typically focus on maximising the productivity of one component of the farming system and evaluating innovations based on averages and plot-scale metrics such as yield per hectare. Yet, for restorative farming practices to be adopted, they not only need to be productive and profitable they also need to be attractive within the broader context of smallholder livelihood systems. This thesis responds to the need for systemic approaches to evaluating innovations and attempts to embrace both the complexity and diversity of smallholder livelihood systems through its methods. Conducted in the context of a large-scale land restoration project working with over 2,500 farmers in the eastern drylands of Kenya, my overarching goal was to assess the impact of on-farm restoration practices (planting basins and tree planting) on the livelihoods of participating households, so as to improve the specificity of recommendations and scaling of restoration efforts.

In Chapter 2, I present various analytical approaches to assessing the efficacy of planting basins for growing maize. In doing so, I demonstrate how even simple arithmetic and translating plot-scale metrics into farm-scale metrics can be a helpful first step towards more farmer-relevant assessments. In Chapter 3, I develop a farm-scale model that extends the results from Chapter 2 across multiple years and explores the impact of planting basins for two households with contrasting resource endowments. Chapters 4 and 5 take a more qualitative and inductive approach, broadening the scope of my assessment to include the role of intrahousehold gender dynamics and aspirations. Combining survey data on decision-making and labour participation with interviews and focus group discussions, I investigate how gender roles and relations influence the uptake of planting basins and tree planting. In Chapter 5, I explore the changing livelihood aspirations of rural women amidst intensifying male outmigration using a novel narrative-based survey tool, contributing to a more nuanced understanding of rural aspirations and the socio-cultural context within which they are embedded.

Although planting basins provided impressive gains in average maize yield, there was strong variability in their performance. For some households, they provided substantial production increases, extra days of food and a potential income boost, while other households faced substantial losses. This variability in performance presents substantial risks for farmers when

basins are promoted as a generalised recommendation. Furthermore, plot-scale metrics such as yield and intensity of adoption overlooked the wider role planting basins play within people's livelihoods, other than maximising yield (e.g., yield stability) and share of benefits amongst household members. Chapters 4 and 5 revealed that heterogeneity also exists in the aspirations of those within households and that women are likely to be important catalysts of agricultural innovation amid the increasing outmigration of men and feminisation of farm management.

Attempting to apply a more systemic approach to evaluating restoration practices, this thesis is interdisciplinary in nature and broad in its scope and use of methods. It brings together alternative approaches to assessing agricultural innovations, and in doing so, stresses the need for development-focused agricultural research to step away from a fixation on differences in mean yield and to embrace variation in innovation performance and complexity of smallholder livelihoods, not avoid it.

Acknowledgements

This thesis would not have been possible without the support of many people. Firstly, I would like to thank my supervisors, Dr Tim Pagella and Dr Leigh Winowiecki, for their insight, encouragement, and patience over the past four years.

I would also like to thank Dr Fergus Sinclair for making this Bangor-ICRAF collaboration possible and for his support throughout; Ana Maria Paez Valencia, an honorary supervisor, for her expertise and collaboration on the gender aspects of this research; Dr Kai Mausch and Dr Dave Harris for the opportunity to join their project team on rural aspirations; Christine Magaju, Esther Kiura, Ibrahim Ochenje, Dr John Nyaga, and Parmutia Makui for their collaboration and team work on many aspects of this research; Dr Jasper Taylor for his guidance and support with using Simile and, along with Dr Neil Huth and Dr Philip Smethurst, for making APSIM-Simile models a reality; and Dr Patricia Masikati for their feedback throughout model development.

This research would also not have been possible without funding from the International Fund for Agricultural Development (IFAD) and European Commission through the project "Restoration of degraded lands for food security and poverty reduction in East Africa and the Sahel: taking successes to scale", grant numbers: 2000000520 and 2000000976 (all chapters), and the CGIAR Research Programme on Forests, Trees and Agroforestry (FTA) (all chapters), the CGIAR Research Program on Grain Legumes and Dryland Cereals (GLDC) (Chapter 5), and the CGIAR Research Program on Policy, Markets and Institutions (PIM) (Chapter 5).

I am also incredible grateful to all the Community Facilitators and enumerators for their support and facilitation in the field, in particular Stephen Maithya, Carolyn Mbuvi, Sylvester Muendo, Silas Muthuri, Francisca Mutua and Mercy Musyoki; to Anne Omollo, Mary-Jude Kariuki, Ann Mbuthia and Caroline Gathoni for their administrative assistance; and to Albanus Mutisya and his team for their excellent translation and transcription services.

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Above all, I am immensely grateful to the many women and men across Makueni, Machakos and Kitui counties whose generosity and patience in sharing their time, knowledge, and insights, made this research possible.

Declaration

I hereby declare that this thesis is the results of my own investigations, except where otherwise stated. All other sources are acknowledged by bibliographic references. This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree unless, as agreed by the University, for approved dual awards.

Yr wyf drwy hyn yn datgan mai canlyniad fy ymchwil fy hun yw'r thesis hwn, ac eithrio lle nodir yn wahanol. Caiff ffynonellau eraill eu cydnabod gan droednodiadau yn rhoi cyfeiriadau eglur. Nid yw sylwedd y gwaith hwn wedi cael ei dderbyn o'r blaen ar gyfer unrhyw radd, ac nid yw'n cael ei gyflwyno ar yr un pryd mewn ymgeisiaeth am unrhyw radd oni bai ei fod, fel y cytunwyd gan y Brifysgol, am gymwysterau deuol cymeradwy.

Signature: Date: 6th June 2022

Authorship Information

The four research chapters of this thesis have been prepared for peer-review publication. Chapter 4 and Chapter 5 have already been published. Chapters 2 and 3 are both in preparation for submission to *Agricultural Systems*. While I am first author and foremost contributor to each publication, several co-authors have been instrumental in conducting the research included in this thesis and in its conceptual design. The author list and references for each publication are outlined below, along with an outline of each author's contribution.

Chapter 2: Crossland, M., Winowiecki, L., Magaju, C., Pagella, T., Ochenje, I., Kiura, E., Nyaga, J., Makui, P., and Sinclair, F. (*in prep*). Assessing variation in the performance and contribution of planting basins to household maize self-sufficiency and income.

Overall project design and implementation of the dryland restoration project and planned comparisons were led by FS and LW. Monitoring surveys were developed by the Kenya project team, namely CM, JN, EK, IO, MP and LW. I provided input on all monitoring surveys and was heavily involved in the design of the OND 2017 survey with JN, CM, LW, and EK. For the OND 2017, I programmed the OND 2017 ODK form with PM; cleaned the data with JN and designed and led the enumerator training workshops with CM. All following surveys (OND 2018 and OND 2019), including enumerator training, data collection and data cleaning, were led by JN, IO, and CM. I conducted all analyses and interpretation of the findings presented in this chapter with input from TP.

Chapter 3: Crossland, M., Pagella, T., Taylor, J., Smethurst., P., Huth, N., Masikati, P., Magaju, C., Winowiecki, L., and Sinclair, F. (*in prep*). Developing and applying a farm-scale model for assessing the impacts of planting basins on smallholder livelihood systems.

I designed and constructed the model. FS and TP, along with JT, PS, NH, and PM, provided input on model scope, specification and scenario selection during various iterations of model development. JT provided technical support during model construction and training in the use of the Simile modelling environment, while PS and NH provided support on the use and parametrisation of APSIM. JT and NH developed the APSIM-Simile interface. LW provided soil data and CM information on local farming systems for model parameterisation. I conducted all scenario analysis and subsequent interpretation of findings with input from TP.

Chapter 4: Crossland, M., Paez Valencia, A.M., Pagella, T., Magaju, C., Kiura, E., Winowiecki, L. and Sinclair, F. (2021). Onto the Farm, into the Home: How Intrahousehold Gender Dynamics Shape Land Restoration in Eastern Kenya. *Ecological Restoration*, 39: 90-107.

I designed the survey questions, interview and focus group discussion guides in collaboration with AMPV and with input from TP, CM, EK and LW. I collected the data with AMPV, CM and EK, and assistance from the community facilitator team. I analysed the data and interpreted the results with input from AMPV and TP. All co-authors, along with guest editors and two anonymous reviewers, provided comments and edits on various versions of the manuscript.

Chapter 5: Crossland, M., Paez Valencia, A.M., Pagella, T., Mausch, K., Dilley, L., Harris, D. and Winowiecki, L. (2021). Women's Changing Aspirations Amid Male Outmigration. Insights from Rural Kenya, 33, 910-932. *The European Journal of Development Research.*

Overall conceptual framing and design of the aspirations survey were led by KM and DH. Myself and AMPV provided input in the final stages of survey design in specific relation to gender. Survey data was collected by a team of trained enumerators. In collaboration with AMPV and input from TP, I designed the interviews and focus group discussions on migration. I collected the interview and focus group discussion data with AMPV and assistance from the community facilitator team. I analysed the narratives and survey and textual data with input from AMPV and TP. All co-authors provided input and comments on the interpretation of the final findings and, along with two anonymous reviewers, provided comments and edits to various versions of the manuscript.

Ethical Statement

All research conducted for this thesis falls under the IFAD-EC Dryland Restoration project led by World Agroforestry (ICRAF), Kenya. Ethical practices regarding the involvement of people have been respected and the study approved by Bangor University Ethical Review Committee. World Agroforestry's guidance on Research Ethics Policy (ICRAF, 2019), Personal Data Protection (ICRAF, 2018a) and Research Data Management (ICRAF, 2018b) was followed. Informed consent was obtained from all human study participants and all participation was voluntary. All information, including any confidential personal data, was captured without identifying data and stored securely in appropriate facilities.

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Abbreviations

AFR100 – African Forest and Landscape Restoration initiative

CGIAR – Consortium of International Agricultural Research Centres

DryDev – Drylands Development

EC – European Commission

FGD – Focus group discussion

FTA – Forests, Trees, and Agroforestry

GLDC – Grain Legumes and Dryland Cereals

ha – hectare

HH – Household

HRE – Higher Resource Endowed

ICP – International Comparison Program

ICRAF – World Agroforestry

IFAD – International Fund for Agricultural Development

kg – kilograms

Ksh – Kenyan Shillings

LDSF – Land Degradation Surveillance Framework

LRE – Lower Resource Endowed

m – metres

mm – millimetres

ODK – Open Data Kit

OxC – Options by context

PC – Planned comparison

PDI – Personal Daily Income

PIM – Policy, Markets and Institutions

PPP – Purchasing Power Parity

RinD – Research in development

SOC – Soil Organic Carbon

SON – Soil Organic Nitrogen

SSA – Sub-Saharan Africa

t – tons

USD – US Dollars

UN – United Nations

Chapter 1: Introduction

1. Farmland restoration and achieving a sustainable future

Land degradation – the loss of or persistent decline in the productivity of land and its capability to provide ecosystem services – presents a major challenge to achieving a sustainable future (Lal et al., 2012). Over 25% of the Earth's land area is estimated to be severely degraded (FAO, 2011) and, despite global efforts to halt land degradation, the area affected continues to increase (Bai et al., 2008; Lal, 2012). This loss of land-based natural capital threatens the livelihoods of over 1.3 billion people worldwide (UNCCD, 2017) and has been estimated to cost the world economy 231 billion USD each year (Nkonya et al., 2016).

Agriculture is by far the most widespread human use of land. It employs over 26% of the world's labour force (ILO, 2020) and occupies 38% of the global land surface (Ramankutty et al., 2008) and uses more soil and water than any other human activity (FAO, 2011). The conversion of natural habitats to agriculture is associated with biodiversity loss (Zabel et al., 2019), greenhouse gas emissions (van Loon et al., 2019), and can significantly contribute to land degradation if management practices are inappropriate (UNCCD, 2017). In many areas of SSA, overgrazing, excessive soil disturbance and the removal of crop residues and limited use of organic inputs such as farmyard manure have led to extensive soil erosion, nutrient depletion and a loss of soil biotic function (ELD and UNEP, 2015; UNCCD, 2017). Degrading farming practices undermine the resource base on which agricultural-based livelihoods and future production depend and jeopardize both local and global food production (UNCCD, 2017). While increasing agricultural production alone does not guarantee food security[1], it is generally agreed that agricultural productivity in SSA will need to increase to achieve the United Nation's (UN) Sustainable Development Goals of ending poverty and hunger (van Ittersum et al., 2016; Pingali et al., 2006; Vorley et al., 2012).

Compared to other regions, SSA has one of the largest gaps between cereal consumption and production, with current farm yields remaining well below potential yields (van Ittersum et al., 2016). In Kenya, for example, current average maize yields oscillate around 1.9 t ha^{-1} while

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[1] In terms of all six dimensions of food security: availability, access, utilization, agency, stability, and sustainability (HLPE, 2020).

water-limited yield potential[2] is estimated at 7.9 t ha^{-1} (GYGWPA, 2021). Past gains in food production in SSA have largely resulted from agricultural extensification - the cultivation of more land – rather than intensification and increased land productivity (Giller, 2020; Jayne and Sanchez, 2021). Meeting the needs of a burgeoning population while avoiding further agricultural expansion will likely require a rapid increase in crop productivity and the rate at which yield gaps are closed (Giller, 2020; van Ittersum et al., 2016). In turn, this will require widespread effort to restore degraded lands and reduce agriculture's contribution to degradation processes.

Land restoration and avoiding further degradation is seen as a critical pathway to achieving multiple global objectives, from improving food security and reducing poverty, to mitigating climate change and conserving biodiversity (Cowie et al., 2018; IPBES 2018). The past decade has seen an unprecedented commitment to restoring deforested and degraded land. Under initiatives such as the Bonn Challenge and the UN Sustainable Development Goals, governments across the globe have pledged to restore hundreds of millions of hectares of degraded land by 2030, while the UN recently declared 2021-2030 the "Decade on Ecosystem Restoration". Under the African Forest and Landscape Restoration initiative (AFR100) which aims to restore 100 million hectares of land by 2030, the government of Kenya alone has committed to restoring 5.1 million hectares of degraded land.

More than two billion hectares of land are estimated to offer opportunities for restoration worldwide, and a large proportion are located in SSA, on or adjacent to agricultural lands (Minnemeyer et al., 2011). Nevertheless, a pervasive challenge to achieving these pledges and reducing agriculture's contribution to land degradation is that restorative farming practices – practices known to sustainably increase production and reduce and reverse degradation processes – are not widely adopted by smallholder farmers (Arslan et al., 2013; Thornton et al., 2018; Walker and Alwang, 2015).

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[2] The Global Yield Gap and Water Productivity Atlas (GYGWPA) uses well-validated crop simulation models to estimate potential yield and water-limited potential yield for a given location based on local weather, soil, and crop management data (GYGWPA, 2021). Yield potential is the yield of a given crop cultivar when grown with nutrients and water non-limiting and effective control of any pests, weeds, and diseases. Unlike yield potential, water-limited yield potential accounts for crop growth being limited by water supply. Water-limited yield potential is the most relevant benchmark for estimating yield gaps for rain-fed crops. While simulated potential yield and water-limited potential yield tend to be higher than those achievable on the ground, the gap between actual and potential yield provides a useful benchmark for assessing the efficacy of agricultural innovations and the degree to which food self-sufficiency may be possible in a location.

2. Matching and tailoring options to context

The argument for this thesis builds on two main points. First, that smallholder farmers in SSA are a diverse group, differing in their demands, opportunities and constraints, and that scaling restoration will require local adaptions of agricultural practices that respond to fine scale variation in farm and farmer circumstances. Second, is that for restorative farming practices to be widely adopted they not only need to be productive and profitable, they also need to be attractive within the broader context of smallholder livelihood systems, which for many households includes both on- and off-farm activities.

In much of SSA, farms are shaped by diverse agroecological conditions, management practices and economic forces, while households and their individuals differ in what they produce, the resources they have access to, and in their knowledge, aspirations, and attitudes towards risk (Giller et al., 2011; Tittonell et al., 2011, 2010). This fine scale variation in social, economic, and agroecological context creates a need for local adaptions of agricultural practices that respond to farmer household demands and constraints (Sinclair and Coe, 2019). Yet, at least until recently, approaches to agricultural research for development have often failed to acknowledge and account for this diversity of farming and farmer circumstances. Instead, common practice has been to promote a limited suite of options across large areas based on mean yield effects from research trials conducted under conditions that fail to represent the realities many smallholders face (i.e., limited resources, time and labour) (Coe et al., 2016; Nelson et al., 2019).

A growing recognition of the need to move away from blanket recommendations and adapt agricultural innovations to local circumstances has led to the development of new approaches to agricultural research for development that aim to match agricultural 'options' to local 'context' (Descheemaeker et al., 2019; Franke et al., 2019; Nelson et al., 2019; Ojiem et al., 2006; Sinclair and Coe, 2019). As defined by Nelson et al. (2019:4), 'options' refers simply to "things that farmers and farming communities can do differently", but may also include actors at multiple scales (e.g., NGOs, and local and national governments) and options that aim to improve the enabling environment for change (e.g., market interventions, extension systems, policies) (Sinclair, 2017). Options interact with 'context' – that is, "the ecological, economic and social situations in which options are used" – to determine their performance (Nelson et al., 2019:4). Gaining a better understanding of the key option by context (OxC) interactions that determine the relevance and suitability of different agricultural options could help researchers and development actors move from providing generic recommendations to more nuanced, context-specific suggestions for farmers (Descheemaeker et al., 2019; Nelson et al., 2019).

Given the large heterogeneity in SSA farming systems, the on-farm performance of agricultural innovations is often variable and dependent on context, presenting considerable gains in production for some farmers and substantial losses for others (Bielders and Gérard, 2015; Coe et al., 2016; Falconnier et al., 2016; Franke et al., 2019). This variability in performance across different contexts presents substantial risks for farmers and a potential barrier to the widespread adoption of restorative farming practices (Coe et al., 2016; Vanlauwe et al., 2019). Identifying the cause of this variation and understanding the environmental and management conditions under which different options perform best (i.e., OxC interactions), could therefore allow for better targeting of technologies to different farming contexts and reduce the risk farmers face when adopting new agricultural technologies (Coe et al., 2014; Descheemaeker et al., 2019; Nelson et al., 2019).

3. Taking a livelihood systems perspective

Current approaches to agricultural research for development have also tended to focus on maximising the productivity of one component of the farm system and evaluating innovations based on plot-scale metrics such as average yield per hectare (Sinclair, 2017; van Ginkel et al., 2013; Vanlauwe et al., 2019). Yet, for restorative farming practices to be adopted they not only need to be productive and profitable, they also need to be attractive within the broader context of smallholder livelihood systems (Harris and Orr, 2014; Sinclair, 2017; Verkaart et al., 2018).

Given the seasonal, risky nature of farming and limitations of small farms and degraded soils, rural households in SSA increasingly pursue diverse livelihood strategies comprising various on- and off-farm activities in order to survive (Barrett et al., 2001; Ellis and Freeman, 2004; Haggblade et al., 2010). Consequently, decisions over resource allocation and investment often involve complex trade-offs between multiple livelihood activities (Giller et al., 2006). While households may derive part of their livelihood from farming and personally identify as farmers, agricultural productivity is unlikely to be the only aspect of their livelihood portfolio they are seeking to maximise. In this light, farmers may be more interested in other performance metrics, such as labour savings, increased resource use efficiencies and yield stability, rather than agricultural productivity alone (Descheemaeker et al., 2019). Indeed, many households may seek to step out of farming completely and focus on local or migratory off-farm income sources (Dorward et al., 2009).

Two widely held assumptions in development-focused agricultural research are: i) that a household's ability to prosper is limited only by the productivity of their farm (Harris and Orr, 2014), and ii) that those who do farming are willing to further invest their time and resources in agriculture (Mausch et al., 2018; Verkaart et al., 2018). Rarely is it considered that households may have other livelihood options or aspirations, or that they may not have enough land to earn a reasonable living from farming alone (Gassner et al., 2019; Mausch et al., 2021, 2018).

In much of SSA, farms are small, families are large, and agriculture may represent only part of a household's total income (Harris and Orr, 2014; Lowder et al., 2016; Verkaart et al., 2018). Even when innovations result in large increases in productivity, the potential for agriculture to reduce poverty at the household level may be limited (Harris and Orr, 2014; Gassner et al., 2019). Switching to a more sustainable farming practice might increase crop productivity by 200%, but what would that mean for a household of five living on half a hectare of land? How many additional days could they feed their family? How much extra money could they earn? How much labour would they save? Could this labour then be used for alternative, more lucrative income activities? Such livelihood outcomes and farm-scale metrics are rarely considered in the evaluation of agricultural innovations.

Taking a more holistic, livelihoods perspective in our evaluations of innovations is likely to give us a much better idea of what works where, by how much and for whom, helping us to match and tailor options to local contexts and household demands (Coe et al., 2014; Descheemaeker et al., 2016;). This thesis thus responds to the need for more systemic approaches to evaluating the performance of agricultural innovations and attempts to embrace both the complexity and diversity of smallholder livelihood systems and the broader social and economic context within which restoration is to occur.

4. The potential of restorative farming practices

Numerous on-farm restoration practices are used and promoted across the African drylands. These restorative farming practices not only aim to increase and maintain agricultural productivity but to reduce and reverse degradation processes and can be broadly categorised into four types of measures (ELD and UNEP, 2015): agronomic measures that improve soil cover (e.g., cover crops and mulches) and soil fertility and organic matter (e.g., farmyard manure), and reduced tillage practices (i.e., non-inversion, planting basins); vegetative measures such as planting grasses and other perennial species and establishing on-farm trees; structural measures including terraces, ditches and other soil and water conservation structures; and lastly, management measures, for example, diversifying crop rotations and improved livestock management (e.g., zero grazing, area enclosures and use of cut and carry).

Many of these mentioned practices, and combinations thereof, have been promoted under the auspice of various sustainable agricultural approaches (e.g., sustainable intensification, agroecology, climate-smart agriculture, conservation agriculture) (HLPE, 2019). Common practices promoted in the drylands of Kenya include agroforestry, conservation agriculture, and use of soil and water conservation structures such as terraces (CGoM, 2019; ELD and UNEP, 2015).

Increasing tree cover on farms (i.e., agroforestry) can enhance land productivity by increasing vegetation cover and protecting soils from erosion, increasing water infiltration, and improving soil fertility and organic matter (Yirdaw et al., 2017). Trees can also provide multiple livelihood benefits, including drought resilience and improved food security and income through the consumption or sale of tree products (van Noordwijk et al., 2018).

Structural measures such as digging trenches and terraces, where soil on sloping lands is excavated to create level areas for cultivation, can help reduce surface run-off and soil erosion. Such measures have been widely used in Northern Ethiopia and are reported to have resurrected degraded watersheds, which now provide young Ethiopians with income opportunities (Watson, 2016; Meaza et al., 2016). Likewise, as documented in the seminal work of Tiffen et al. (1994), “More people, less erosion”, extensive terracing on sloping lands has helped abate severe soil erosion in eastern Kenya.

Conservation agriculture (CA) is a farming approach that aims to address soil degradation and improve production through the adoption of three agronomic principles: i) minimising tillage; ii) maintaining continuous soil cover (i.e., cover crops, mulches); and iii) diversifying crop rotations (Giller et al., 2009). CA is commonly promoted as a package of practices. In southern and eastern Africa these practices include planting basins or ripping the soil with an adapted plough when draft animals are available, leaving crop residues in the field and cereal-legume crop rotations (Arslan et al., 2013).

While restorative farming practices offer potential benefits for smallholder farm households, as with many agricultural innovations, there is a lack of understanding of when and where specific practices are most likely to benefit people's livelihoods. Data on the cost of implementing restoration practices are rare, and the socio-economic benefits of restoration remain poorly understood (Yirdaw et al., 2017). Furthermore, the performance of many restoration practices is variable, and what works for one farm may not work for another (Giller et al., 2011). For instance, although typically promoted as a package, all three components of CA are not always adopted by smallholder farmers (Rodenburg et al., 2021). Reasons include lack of labour, limited access to inputs such as pesticides and the high value of crop residue as a feed source for livestock (rather than mulch) (Giller et al., 2009). Likewise, smallholder farmers may have limited access to farmyard manure due to low livestock ownership, and sources of organic inputs can be variable and low in quality (Palm et al., 2001). One of the driving hypotheses behind this thesis is that, while the restoration of degraded agricultural lands will likely provide substantial benefits to rural livelihoods, restorative farming practices must be adapted to local farming systems and the constraints farmers face.

5. The Dryland Restoration Project

The research presented in this thesis draws on several datasets most of which were collected under a large-scale dryland restoration project: "Restoration of degraded land for food security and poverty reduction in East Africa and the Sahel: taking successes in land restoration to scale (2015-2020)" (hereinafter referred to as 'the project') (World Agroforestry, 2020). This project sought to improve the livelihoods and food security of smallholder farm households living in African drylands by restoring degraded land and returning it to effective and sustainable tree, crop, and livestock production. To achieve this, the project employed a co-learning research 'in' development (RinD) approach (Figure 1.1), whereby researchers, farmers and development actors collaborate to systematically test promising innovations across a range of social and agroecological contexts to better understand which options best suit different farming and farmer circumstances (Coe et al., 2014; Sinclair and Coe, 2019).

In contrast to more retrospective approaches of research 'for' development, where innovations are typically developed on research stations before scaling to farmers' fields, research 'in' development embeds research within development activities and supports the testing of innovations on farmer's fields (Coe et al., 2014). This allows for increased understanding of what works best where and for whom in terms of both agroecological and socio-economic outcomes, while bringing options to farmers at scale (Coe et al., 2014). A key component of the RinD approach is the use of participatory monitoring and evaluation. This includes the use of planned comparisons (PCs), where farmers select and compare the performance of different innovations and corresponding variations thereof, on their own farms (Coe et al., 2017a; Nelson et al., 2019; Nelson and Coe, 2014).

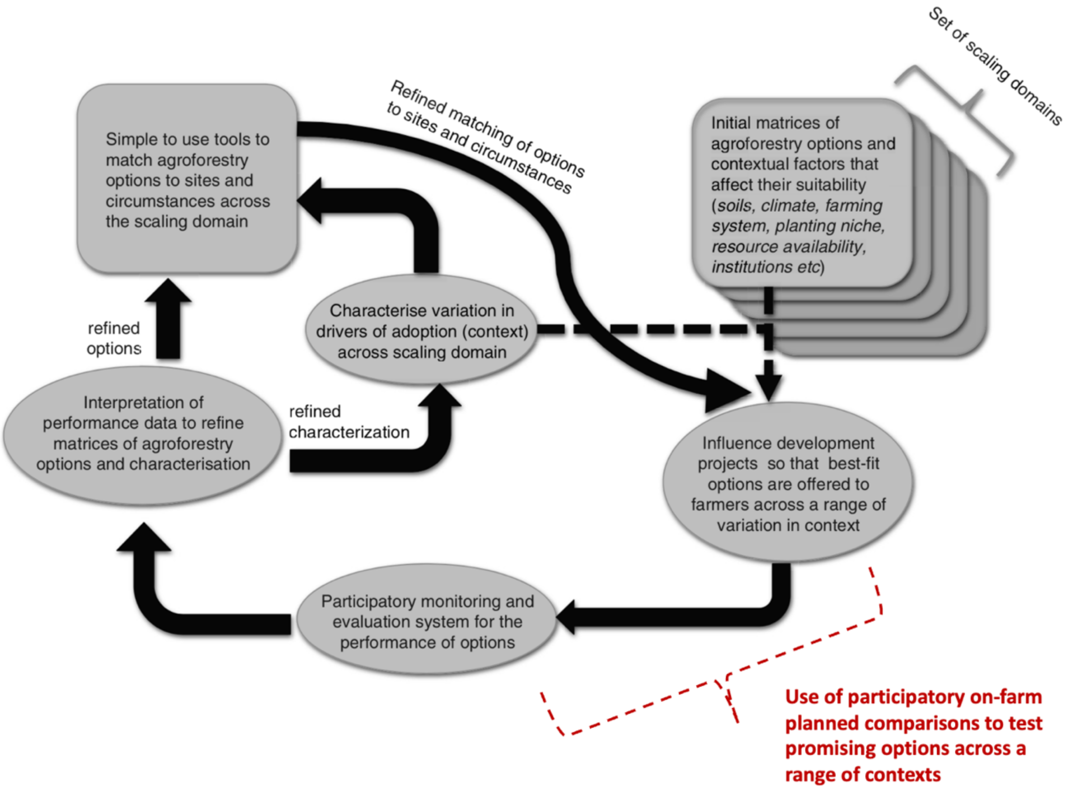

Figure 1.1 The co-learning 'research in development' paradigm whereby research is embedded within and informs development activities. Image adapted from Coe et al. (2014).

Over a five-year period (2015-2020), the project worked with over 2,500 smallholder farmers in the eastern drylands of Kenya to conduct planned comparisons of promising on-farm restorative practices. The first planned comparison involved on-farm tree planting. A significant barrier to establishing trees in the drylands is low seedling survival caused by erratic climate, inappropriate management practices and use of ecologically unsuitable species (De Leeuw et al., 2014; Derero et al., 2020; Ndegwa et al., 2017). The project thus worked with farmers to compare the effect of different planting and management practices on seedling survival, including planting hole size, planting with/without manure and different watering regimes (Magaju et al., 2020, 2019a, 2019b). The second planned comparison involved the use of planting basins. While basins have long been promoted in arid areas of SSA, questions remain regarding the most appropriate size of basin and soil treatment for different farming contexts (Danjuma and Mohammed, 2015). Farmers, therefore, compared maize yield (*Zea mays. L.*) in different basin sizes and manure treatments against their usual tillage practices of ox plough or hand hoe cultivation.

6. Focus region

This research focuses on three counties in the drylands of eastern Kenya – Kitui, Machakos and Makueni counties – together, locally known as Ukambani and home to the Akamba community. Rainfall in the region shows a distinct bimodal distribution, receives an average seasonal rainfall between 250-400 mm, and experiences frequent droughts and considerable inter-seasonal variation in precipitation (Kiilu and Wambugu, 2001).

Despite the area's marginal potential for agriculture, people's livelihoods depend heavily on farming and typically combine rain-fed agriculture with livestock keeping (Ifejika Speranze et al., 2008). The main food crops grown by households are maize, beans, cowpea, and pigeon pea. Farm labour is largely unmechanised, relying on hand labour and ox-plough cultivation. Other on-farm activities include horticulture, agroforestry, and dairy farming, primarily using a zero or semi-zero grazing system (e.g., where crop residues and cut grasses and tree fodder are fed to animals kept in on-farm enclosures, locally known as *bomas*) and limited use of communal grazing areas. The area is also well known for tree fruit production. Makueni County is the leading producer of mangos in Kenya and has a fruit processing plant that supports an estimated 12,000 local smallholders through value addition and market linkages (Wangu et al., 2020).

Due to the subdivision of land and population growth, farms are generally small with an average farm size of 1.2 hectares in Makueni (GoMC 2018), and 1 hectare in Machakos (GCoM, 2018), and 4.4 hectares in Kitui (CGoK, 2018). To help ensure land tenure security for smallholders, all three counties have active land titling and digitisation programs. Around 30% of landowners in Makueni and Machakos now have title deeds, compared to only 17% of landowners in Kitui (CGoK, 2018, CGoMa, 2018, CGoMb, 2018). Numerous gazetted and ungazetted forests are found in the region, and many households depend heavily on forest products and services for their livelihood (Mwikali et al., 2021). Heavy reliance on fuelwood and charcoal for household energy needs and income has led to many private farmlands, community lands, and local forests becoming depleted of trees (Ndegwa et al., 2020).

The region has a history of high population growth, land shortages and reoccurring challenges with land degradation, including deforestation, soil erosion, declining soil fertility and overgrazing (McCown and Jones, 1992; McCown et al., 1992). Past efforts to curb degradation in the region have focused on extensive terracing in hilly areas to reduce soil erosion, enhanced crop-livestock integration, improved crop rotation, and reduced reliance on communal grazing areas (McCown and Jones, 1992; McCown et al., 1992; Tiffen et al., 1994).

Yet, despite past successes, land degradation is a reoccurring challenge. Consequently, many households are food insecure and rely on external food aid and food-for-work programmes (Ifejika Speranze et al., 2008; KFSSG, 2019). In response to poor agricultural productivity and limited local employment opportunities, wage labour migration (especially by men) is a common and long withstanding livelihood strategy in the region (GoMC 2019; Ifejika Speranza, 2006; Tiffen et al., 1994). The Ukambani region has been an area of continued development focus for both international and national institutions (Rocheleau et al., 1995), and since the devolution of the Kenyan government in 2010, the administrative counties are responsible for providing agricultural extension services and supporting agricultural development at the county level.

7. Thesis aims and objectives

The overarching aims of the research were to determine how interventions to restore degraded farmland can and cannot influence the livelihoods of smallholder farm households in the drylands of eastern Kenya, and the extent to which they can, directly and indirectly, contribute to improving household food security and reduce poverty and advance gender equality.

To achieve these aims the following objectives were addressed:

1) Understand variability in the performance of restorative farming practices across farms, and evaluate the consequences of this variation for livelihood outcomes (i.e., food self-sufficiency, income and resource-use efficiency) and the targeting of restoration options (*Chapters 2 & 3*);
2) Gain insights into the wider social context within which land restoration is to occur, including the role of intrahousehold gender dynamics and aspirations in the trial and uptake of restoration practices and agricultural investment more broadly (*Chapters 4 & 5*), and;
3) Use this understanding to develop recommendations for conducting research for development and land restoration approaches that can improve food security, reduce poverty, and advance gender equality (*Chapters 2, 3, 4, 5 and 6*).

The driving hypothesis behind these objectives was that land restoration options can improve food security and reduce poverty for rural people in drylands, but need to be locally adapted, combined and matched to fine-scale variation in livelihood context to do so.

8. Thesis structure

Attempting to take a more holistic approach to the assessment of restoration practices, this thesis is broad in its scope and use of methods (Table 1.2). In Chapter 2, we analyse maize yield data from on-farm trials of planting basins to understand and evaluate farm-scale variability in performance. In Chapter 3, we develop a farm-scale model that extends the results from Chapter 2 across multiple years and assesses the *ex-ante* impacts of planting basins on the livelihood outcomes of two households with contrasting resource endowment. Through working with farmers to conduct the planned comparisons and hearing women's stories of their increasing role as farm managers, the importance of gender dynamics and intrahousehold relations became increasingly evident. Chapters 4 and 5 therefore take a more qualitative approach, broadening the scope of our assessment to include the role of intrahousehold gender dynamics and livelihood aspirations. In Chapter 4, we combined survey data on decision-making and labour participation with semi-structured interviews and focus group discussions to explore how gender roles and relations within households can influence the uptake and use of restoration practices. In Chapter 5, we took a wider view and explored rural men's and women's opportunities and aspirations, both in and out of farming, using SenseMaker®, a novel narrative-based survey tool. The research chapters of this thesis can thus be seen as a progression from the field to the community scale, and from assessing the efficacy of restoration practices to understanding the wider social context within which restoration is occurring (Figure 1.2). Lastly, in Chapter 6, we reflect on the main findings of the research chapters and their implications for development-focused agricultural research and discuss how the methods and approaches used in this thesis could be integrated to provide more systemic evaluations of agricultural innovations.

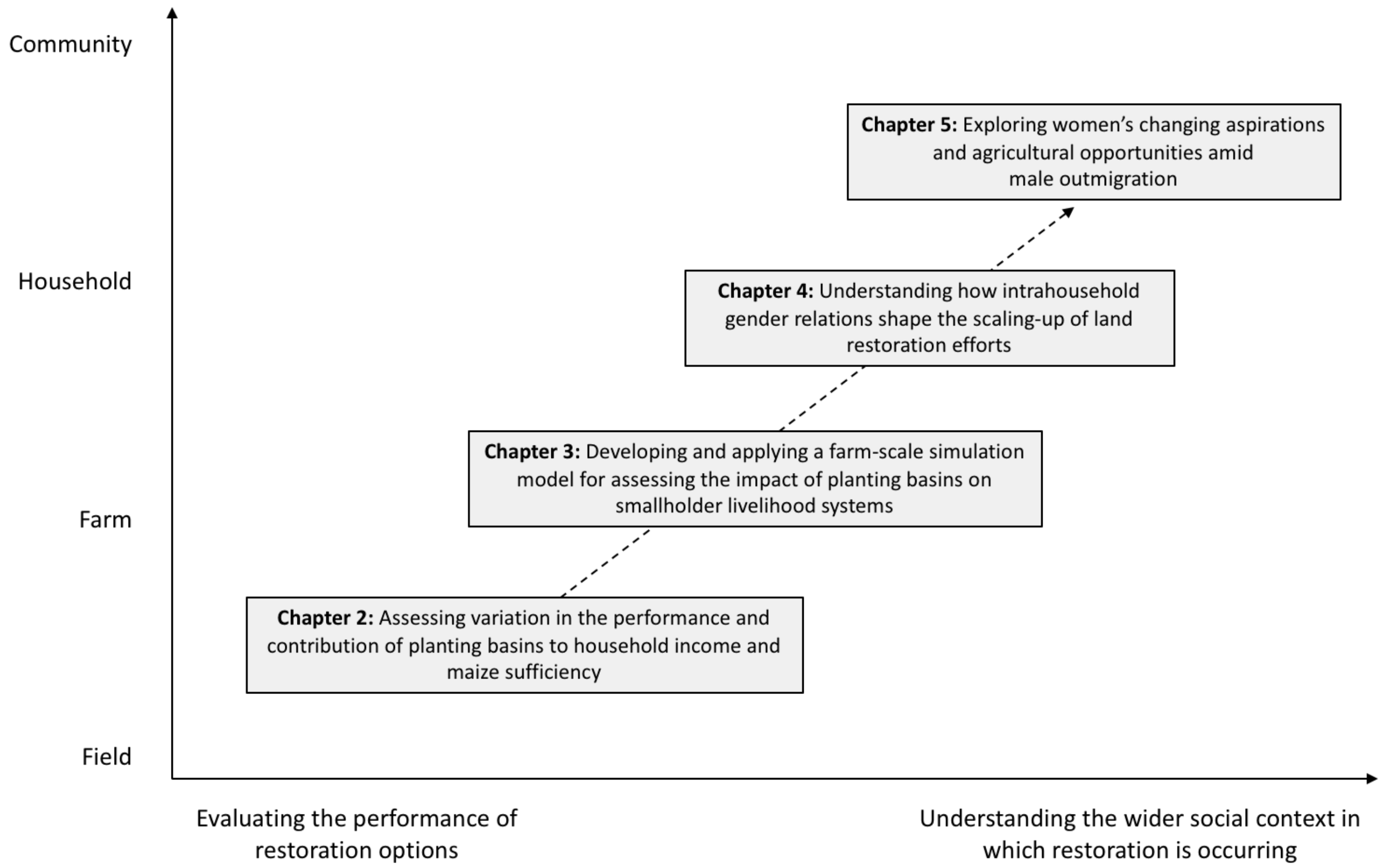

Figure 1.2 Progression of thesis chapters in terms of their scale and scope.

Table 1.1 Thesis structure and methods by chapter and objective.

Chapter	Description	Methods	Objectives
2. Assessing variation in the performance and contribution of planting basins to household income and maize sufficiency	Analysis of maize yield data from on-farm trials conducted with over 1,500 farmers testing planting basins.	Descriptive statistics and use of significance tests (e.g., Wilcoxon Rank sum test); linear mixed models; cumulative frequency curves; profitability analyses; and use of farm-scale metrics including personal daily income and days of maize grain self-provision.	1
3. Developing a farm-scale simulation model for assessing the impact of planting basins on smallholder livelihood systems	Ex-ante assessment of the impact of planting basins on the livelihood outcomes of two households with contrasting resource endowment.	Dynamic systems simulation using APSIM and Simile modelling environments; scenario analysis and profitability analyses; and farm-scale metrics including personal daily income and days of maize grain and stover self-provision.	1 & 2
4. Understanding how Intrahousehold gender dynamics shape the scaling-up of land restoration efforts	Gender analysis of two restorative farming practices (tree planting and planting basins) and their impact on household decision-making and division of labour.	Descriptive analysis of survey data on household decision-making and labour and use of significance tests (e.g., Fisher's exact tests); qualitative analysis of focus group discussions (including the use of vignettes); and interview data.	3
5. Exploring women's changing opportunities and aspirations amid male outmigration	Analysis of men's and women's livelihood aspirations in Makueni County.	Qualitative analysis of self-told visions for the future collected using SenseMaker® - a novel narrative-based survey tool; focus group discussions; semi-structured interviews; and descriptive analysis and use of significance tests (e.g., Wilcoxon Rank sum) for quantitative survey questions.	3
6. Synthesis and conclusion	Reflections on work completed, lessons learnt and recommendations.	Review of research chapters.	4

Chapter 2: Assessing variation in the performance and contribution of planting basins to household maize self-sufficiency and income

An adapted version of this chapter is in preparation for submission to Agricultural Systems.

1. Introduction

The drylands are one of the most susceptible biomes to land degradation, with an estimated 10-20 percent of all drylands having already been degraded (MEA, 2005). They are home to over two billion people, who suffer the world's highest incidence of poverty and depend on ecosystem services more than those living in any other ecosystem (MEA, 2005). In sub-Saharan Africa (SSA), drylands make up 58% of total land area, account for 70% of croplands and are home to roughly 425 million people (Cervigni and Morris, 2016).

A major driver of dryland degradation is the use of unsustainable agricultural practices – for example, farming practices that do not replenish soil nutrients and that lead to soil erosion, including inappropriate land preparation, removal of crop residues and limited use of organic inputs such as farmyard manure (Gitau et al., 2006; Rockström et al., 2009). As a result, cultivated lands are often characterized by nutrient-depleted, crusted soils, low in organic carbon and prone to erosion and compaction. Meeting the needs of a growing population while reducing the contribution of agriculture to dryland degradation will require widespread uptake of restorative farming practices – that is, practices that not only increase agricultural productivity but that reduce and reverse degradation processes.

One such practice increasingly promoted in SSA drylands, including those in Kenya, is the use of planting basins (Kimaru-Muchai et al., 2020; Muriu-Ng'ang'a et al., 2017; Ndeke et al., 2021). Planting basins, also commonly known as Zaï pits, are a simple soil and water conservation technique where small pits are dug, usually in a grid formation, and crops planted within them (Figure 2.1). These basins can increase crop yields in several ways. By capturing surface water run-off, they reduce soil erosion and concentrate water at the crop root zone, prolonging moisture availability and helping to bridge intra-seasonal dry spells during crop development. In areas where soils have become compacted, the process of excavating basins breaks through soil crusts and hard plough pans, increasing infiltration. Additionally, compost or farmyard manure is usually added to the pits, further improving soil texture and nutrient availability. Substantial yield increases have been reported in arid and semi-arid areas for a variety of crops when planting basins are used (Table 2.1). Yet, despite these impressive yield gains, adoption rates have been slow and piecemeal and questions remain regarding the tangible benefits to smallholder farm households (Arslan et al., 2013; Corbeels et al., 2014; Giller et al., 2009).

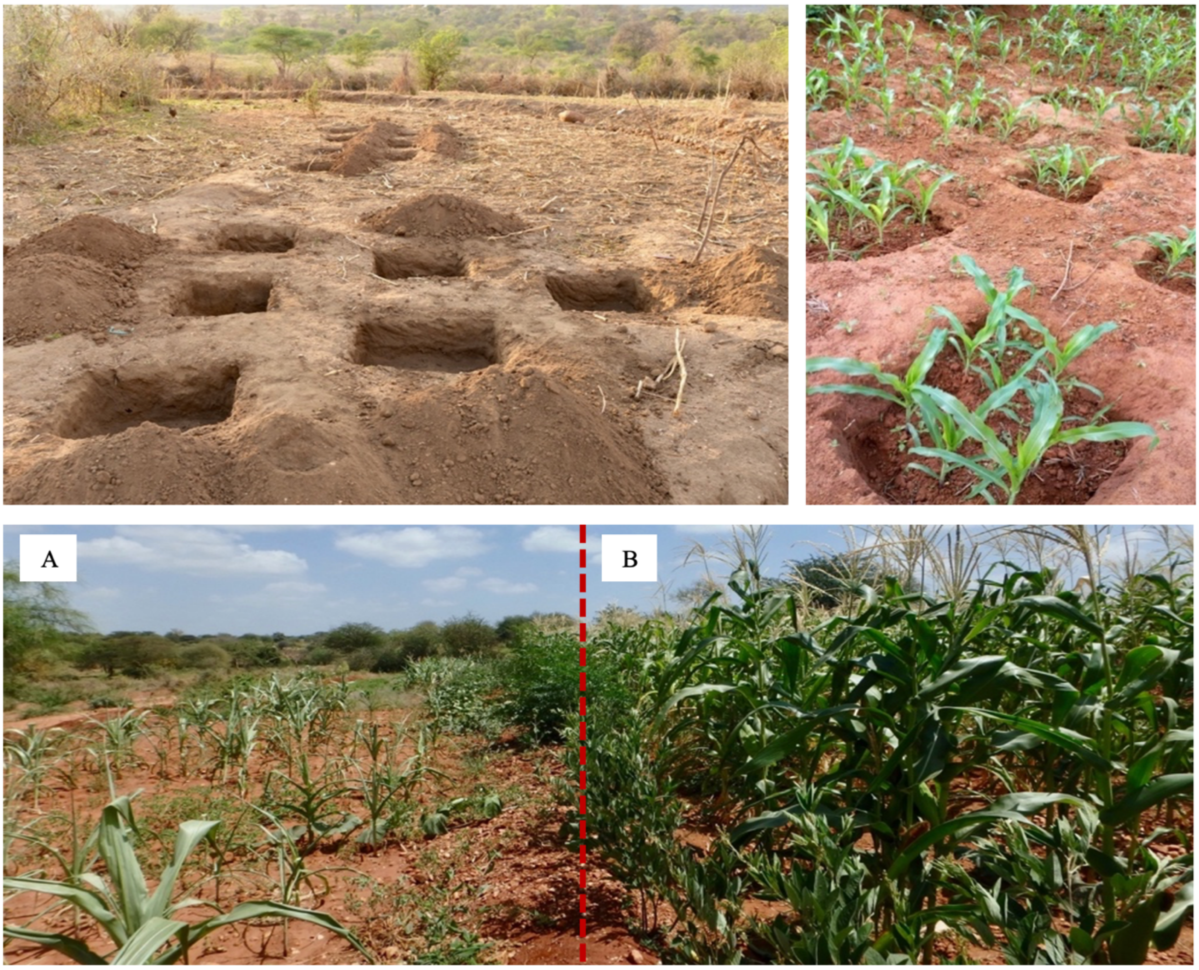

Figure 2.1 Top panel: Examples of planting basin design and arrangement as implemented in this study (Photos: ICRAF/Ake Mamo). Bottom panel: on-farm comparison between farmer's usual tillage practice (A) and planting basins (B) for growing maize (Photos: Mary Crossland).

Given the large heterogeneity of agro-ecologies and farm and farmer circumstances across SSA, planting basins are unlikely to provide a one-size-fits-all solution (Giller et al., 2009; Nyanga et al., 2012). For example, in a review of studies evaluating the performance of basins (Table 2.1), reported mean yield increases for maize ranged from less than 100 kg ha^{-1}, and even yield reductions, to over 5 t ha^{-1}. This variation in performance is likely driven by interactions between planting basins and local agroecological context. For example, in areas where water availability limits crop yields, basins may have a positive yield effect, while under more humid conditions and on poorly draining soils, basins may result in waterlogging and depressed yields (Danjuma and Mohammed, 2015; Mupangwa et al., 2008; Nyagumbo et al., 2016).

Evaluations of basin performance have largely relied on mean yield effects derived from trials involving limited numbers of farmers (Table 2.1). Although widely quoted by agricultural researchers, average statistics such as differences in mean yield can hide considerable variation in the size of treatment effect for different farmers (Coe et al., 2016; Vanlauwe et al., 2019). For example, the use of planting basins may present substantial gains for some households, while others may face risk of substantial losses. This variation in treatment effect poses a considerable risk to farmers when agricultural innovations are promoted and adopted as generalised recommendations (Coe et al., 2016; Vanlauwe et al., 2019). Understanding the sources of this variation could thus help provide tailored recommendations with more reliable outcomes and adapt innovations to different farming contexts and farmer circumstances (Coe et al., 2016). In our summary of studies assessing the efficacy of basins (Table 2.1), only two explicitly acknowledged variation in the performance of basins and the potential risk this poses for farmers (Mupangwa et al., 2017; i.e., Ngoma et al., 2015), and neither attempted to explore the potential sources of this variation nor the within-farm yield differences as experienced by individual farmers.

Studies assessing the performance of planting basins have also largely relied on plot scale metrics, such as yield per hectare, and assume positive yield increases will result in positive outcomes at the household scale (Table 2.1). Yet, in much of sub-Saharan Africa, farms are small and families are large, meaning substantial gains in yield at the plot scale do not necessarily translate into substantial production gains at the farm scale (Harris and Orr, 2014). While some studies assessed the profitability of planting basins, often in terms of gross margin per hectare, few attempted to translate these gains into farm-scale metrics and the specific benefits households and their members can expect to receive – for example, in terms of additional days of food self-provision or increased income per capita. Considering the impact of innovations at the household scale is particularly pertinent in relation to their ability to address poverty and food insecurity, with the potential for innovations to lift households out of poverty likely limited by small farm sizes and large family sizes (Harris and Orr, 2014). For instance, using basins might well increase crop yield by 200% but what would that mean for a household of five living on half a hectare of land? How many additional days could they feed their family? How much extra money could they earn? How much labour would they save? Such livelihood outcomes and farm-scale metrics are rarely considered when developing and scaling agricultural innovations.

Given that planting basins are typically dug by hand and are labour-intensive, an important question is whether yield gains from their use are sufficient to offset the additional labour costs. For example, in Zambia, Ngoma (2018) found that given low levels of uptake, yield increases from basins, although large, did not necessarily translate into increased income or food self-provision and that for many farmers yield gains from basins are insufficient to offset the additional costs associated with their use. In sub-Saharan Africa, rural households are increasingly choosing to pursue diverse livelihood strategies comprising various on- and off-farm activities in order to survive. Consequently, their decisions over resource allocation and investment often involve complex trade-offs between multiple livelihood activities. For many households, this includes both on- and off-farm activities. Agricultural innovations thus not only need to be attractive compared to existing and alternative farming options, but also off-farm income opportunities. Against this backdrop of often complex trade-offs between different livelihood activities, returns to labour are likely to be a key consideration to households who have alternative options. Taking a livelihoods perspective to the evaluation of innovations is thus likely to give a much better idea of whether they are likely to be attractive and what works where and for whom, helping us to match restoration options to local contexts and different types of household (Coe et al., 2014; Descheemaeker et al., 2019).

Questions also remain regarding the most appropriate and cost-effective basin designs for various contexts. In our summary of evidence on the efficacy of basins, we see large variation in the design of planting basins assessed, from basins as small as 15cm in diameter to over 50cm in diameter. Some studies even fail to specify the size of the basins considered. Given the role of basins in collecting surface water run-off, such design considerations are likely to be critical factors in their performance under different agroecological contexts. A common recommendation is that basins are best suited to arid and semi-arid conditions in sites with well-draining soils and receiving rainfall of less than 800 mm per annum due to the pits flooding and becoming waterlogged and thus negatively affecting crop growth (Mupangwa et al., 2008; Nyanga et al., 2012; Schuler et al., 2016). Yet, there is some evidence to suggest that larger basins could work effectively for higher rainfall areas commonly thought to be unsuitable for basins (e.g., Amede et al., 2011).

In this study, we present various analyses using data from on-farm trials conducted with 1,280 households in Kenya on the efficacy of different sizes of planting basin for growing maize. Aiming to address the above knowledge gaps and improve recommendations for smallholder farm households, our objectives were to: i) understand variability in treatment effect across farms and the risk associated with the uptake of basins, ii) assess the potential sources of this variation, and iii) evaluate the potential impact of planting basins on household income and maize self-sufficiency.

Table 2.1 Summary of evidence on the efficacy of planting basins.

Reference	Country	Study type[1]	No. farmers	Crop	Basin innovation tested			Annual rainfall (mm)	Mean yield increment[1]		Additional metrics assessed			
					Width (cm)	Depth (cm)	Additional inputs used[2]		t ha^{-1}	%	Profitability analysis	Returns to labour	Farm-scale metrics	Variability in performance
(Schuler et al., 2016)	Burkina Faso	On-farm	16	Sorghum Millet	20-30	10-20	Manure & fertilizer	400-800	0.32 0.59	61 213	Yes	Yes	Yes	No
(Rockström et al., 2009)	Tanzania Zambia	On-farm	44 66	Maize	?	15	Fertilizer None	300-700	0.85 0.35	39 111	No	No	No	No
(Muli et al., 2017)	Kenya	On-station		Maize	?	?	Manure	450-700	1.50	167	Yes	No	No	No
(Mazvimavi and Twomlow, 2009)	Zimbabwe	On-farm	232	Maize	15	15	Manure & fertilizer	450-650 650-800 >750	1.43 0.59 2.53	156 46 330	Yes	Yes	No	No
(Haggblade and Tembo, 2003)	Zambia	On-farm	125	Millet	?	?	Manure	743	1.72	128	Yes	Yes	No	No
(Malesu et al., 2007)	Malawi	?	?	Cotton	?	?	?	?	2.77	100	No	No	No	No
(Amede et al., 2011)	Ethiopia	On-farm On-farm	3 3	Potatoes Beans	50 50	45 45	Manure & fertilizer	1350	? ?	2000 250	No	No	No	No
(Kodzwa et al., 2020)	Zimbabwe	On-station		Maize	?	15	None	875	0.65	13	No	No	No	No
(Mupangwa et al., 2017)	Zimbabwe	On-farm	130	Maize	15	15	Mulch	450-650 500-800 750-1000	-0.48 0.59 -0.19	-15 17 -9	Yes	Yes	No	Yes
(Mashavakure et al., 2018)	Zimbabwe	On-station		Maize	15	15	Fertiliser	844 680	3.15 5.09	85 111	No	No	No	No
(Mvumi et al., 2017)	Zimbabwe	On-farm	179	Maize	?	?	Fertilizer	< 500	0.52	118	Yes	Yes	No	No
(Ngoma et al., 2015)	Zambia	On-farm	47,950 plots	Maize	?	?	Fertilizer	1020	0.19	?	No	No	No	Yes
(Nyagumbo et al., 2015)	Malawi Mozambique	On-farm	360 144	Maize	15 15	15 15	Fertilizer	500-800 800–1200	0.28 0.08	10 3	No	No	No	No
(Oduor et al., 2021)	Kenya	On-station		Cowpea	60	45	Manure	? 677	0.17 0.39	25 66	No	No	No	No
(Siziba et al., 2019)	Zimbabwe	On-farm	102	Maize	?	?	?	?	0.47	25	No	No	Yes	No
(Bunderson et al., 2017)	Malawi	On-farm	422	Maize	15-35	20	Manure	?	?	11-70	Yes	Yes	No	No

[1] 'On-farm' refers to data collected from farmers' fields in general, not necessarily just formal on-farm trials.
[2] 'Fertilizer' refers to use of inorganic fertilizers.

2. Methods

Our study draws on several datasets collected under a dryland restoration project: "Restoration of degraded land for food security and poverty reduction in East Africa and the Sahel: taking successes in land restoration to scale" (hereinafter referred to as 'the project') (World Agroforestry, 2020). The project sought to improve the livelihoods and food security of smallholder farm households living in African drylands by restoring degraded land, and returning it to effective and sustainable tree, crop and livestock production. To achieve this, the project employed a research in development approach, whereby researchers, farmers and development actors collaborate to systematically test promising innovations across a range of social and agroecological contexts to better understand which options best suit different farming and farmer circumstances (Coe et al., 2014; Sinclair and Coe, 2019). A key component of this approach is the use of planned comparisons (PCs), where farmers select and compare the performance of different innovations and corresponding variations thereof, on their own farms (Coe et al., 2017; Nelson et al., 2019; Nelson and Coe, 2014). Over a five-year period (2015-2020), the project worked with over 2,500 smallholder farmers in the eastern drylands of Kenya to conduct planned comparisons of on-farm restorative practices. These comparisons included on-farm tree planting and the use of planting basins for maize production. The following study focuses on data collected from 1,280 farmers involved in the planting basin planned comparison between 2017 and 2019.

2.1 Site description

The study was conducted with farmers across six sub-counties in Machakos, Makueni and Kitui counties in eastern Kenya (Figure 2.2). This semi-arid region is characterised by small-scale, rain-fed mixed farming and subject to frequent drought and crop failures caused by increasingly unreliable rainfall (KNBS, 2019). Agricultural productivity is limited by extensive land degradation and many rural households experience food insecurity (KFSSG, 2019). Maize is the main food crop grown by households for home consumption followed by various legumes, fruits, and vegetables. Rainfall distribution is bimodal with two seasons per year: the long rains typically falling over March-April-May (MAM) and the short rains falling over October-November-December (OND). The OND season is the main growing season for maize in the study area given its comparative reliability.

The six sub-counties cover a range of socio-ecological conditions and vary in average annual precipitation and temperatures (Table 2.2) and their proximity to urban centres (Figure 2.2). The six sites therefore vary in their connectivity to markets, off-farm employment opportunities and agricultural potential. Mwala and Yatta (Machakos County) are generally the wettest counties, located at higher altitudes and present more favourable agroecological conditions compared to the other sites. They are also relatively well connected to urban centres including Nairobi and growing towns such as Matuu. Mwingi East and Kitui Rural (Kitui County) on the other hand are more remote, especially Mwingi East, with fewer off-farm employment opportunities and comparatively high poverty rates. Kibwezi East and Mbooni East (Makueni County) have the driest climates. Kibwezi East in particular experiences high levels of soil erosion and many project households farm rocky soils with low soil organic carbon. The site is also located close to a main highway connecting Mombasa and Nairobi, and off-farm employment and labour migration are common, especially among adult male household members (Ifejika Speranza, 2006, see also Chapter 4 and 5).

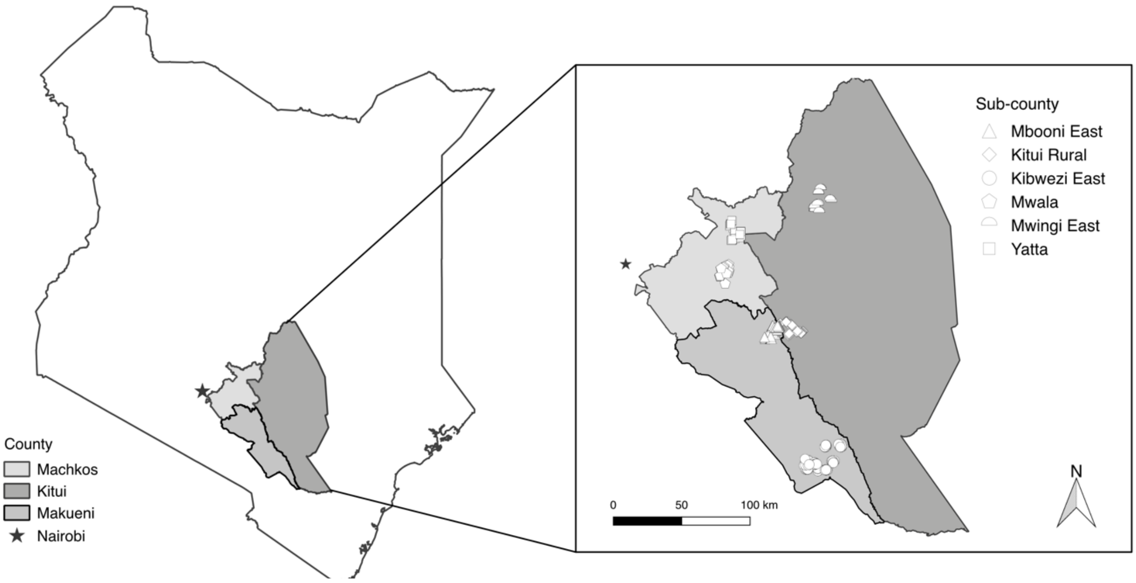

Figure 2.2 Map of project sites and participating households in Machakos, Makueni and Kitui counties.

Table 2.2 Climatic information for study sites. Statistics presented: mean (SD) annual precipitation (Funk et al., 2015) and annual temperature (Sparks, 2018).

	Machakos County		**Makueni County**		**Kitui County**	
	Mwala	**Yatta**	**Kibwezi East**	**Mbooni East**	**Mwingi East**	**Kitui Rural**
Annual average precipitation (mm)	866.6 (198.4)	710.9 (189.0)	609.9 (166.9)	689.7 (187.0)	768.3 (220.2)	617.9 (163.6)
Annual average temperature (C°)	21.2	23.0	25.2	23.1	25.4	23.1

2.2 Planting basin planned comparison

During a community visioning and planning process held by the project in 2015, farmers across the study area raised questions regarding the most appropriate size of planting basin and fertilization method for different farming contexts (Sola et al., 2017). Thus, the objective of the planting basin planned comparison was to better understand which sizes of basin and associated fertility management practices perform best where and for whom. Within each sub-county, 6-10 target villages were randomly selected and resident farmers invited to participate. The only criterion being farmer's willingness to take part in the comparison. Given the project's focus on scaling restoration efforts, new farmers were able to join the comparison at any point and existing participants regularly encouraged to invite their friends and neighbours to enrol.

As part of the planned comparison, farmers were asked to divide small areas of their farm into treatment plots and to compare maize yield from different sizes of basin and manure treatments against their usual tillage practices (Wafula et al., 2016). Each season, farmers were trained on how to construct planting basins and how to set up the planned comparison during farmer workshops. Farmers then implemented the planned comparison on their own farms and were given choice over which and how many options to compare. On each farm the planned comparison was implemented as a non-replicated trial, each farmer therefore forming a replicate. Participating farmers tested three main sizes of basin: 30x30cm (small basins); 60x60cm (medium basins), and 90x90cm (large basins) – all 45 cm in depth (Table 2.3). For all three sizes, farmers were advised to space basins 60cm apart and in a grid formation. The project then worked with farmers through a team of community facilitators and trained enumerators to monitor the performance of the various options tested in terms of maize production and their cost-effectiveness.

Table 2.3 Dimensions and advised basin density per hectare for the three basin sizes tested as part of the planned comparison.

Basin size	Dimensions (cm)	Depth (cm)	Advised number of basins per hectare
Small	30x30	45	12,346
Medium	60x60	45	6,944
Large	90x90	45	4,444

2.3 Data collection and analysis

Data was collected from a total of 1,459 individual households taking part in the planting basin planned comparison between 2017 and 2019. A monitoring survey was conducted at the end of each OND growing season to collect information on the planned comparison, including planting dates, plot management (maize variety, manure application, farmers usual tillage practice), labour input, and maize yields. The three monitoring seasons varied in rainfall conditions with OND 2017 experiencing poor rainfall; OND 2018 being a relatively good rainfall year, and OND 2019 one of the wettest seasons on record (Wainwright et al., 2021) (Figure 2.3). From the 1,459 households surveyed, a total of 4,366 plots were assessed over the three monitoring seasons. Most farmers had only two plots they were comparing: one plot with planting basins of a specific size (treatment) and another plot managed using their usual tillage practice (control) (i.e., ox plough or hand hoe cultivation). Although farmers were encouraged during training workshops to include manure application as part of their planned comparison, few farmers included this option as part of the comparison.

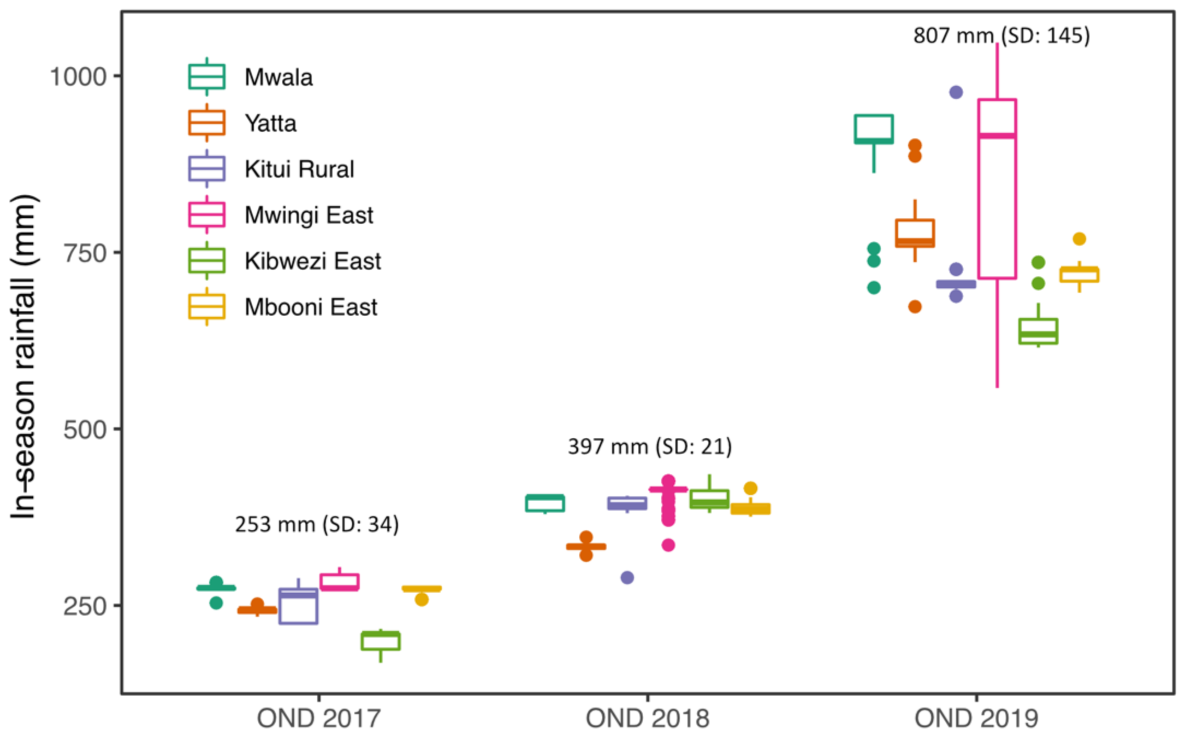

Figure 2.3 Total in-season rainfall (i.e., total rainfall falling between 1st October to 31st December) for each household location. Data sourced from CHIRPS (Funk et al., 2015). Mean and standard deviation for each season shown.

In OND 2017, farmers harvested earlier than expected due to poor rains and direct yield measurements were not possible. Maize yields for 2017 are thus based on farmer estimated yield, where each farmer was asked to estimate how many kilograms of maize they had harvested from the total area of each treatment plot. These estimates were then scaled to metric tonnes per hectare. In OND 2018 and OND 2019 yield measurements involved destructive sampling. For each plot containing planting basins, a minimum of five basins were randomly selected and all maize cobs and stover removed and weighed separately (Figure 2.4). For each farmer practice plot, all maize cobs and stover were removed from a 25m^2 quadrat located at the centre of the plot and weighed separately (Figure 2.4).

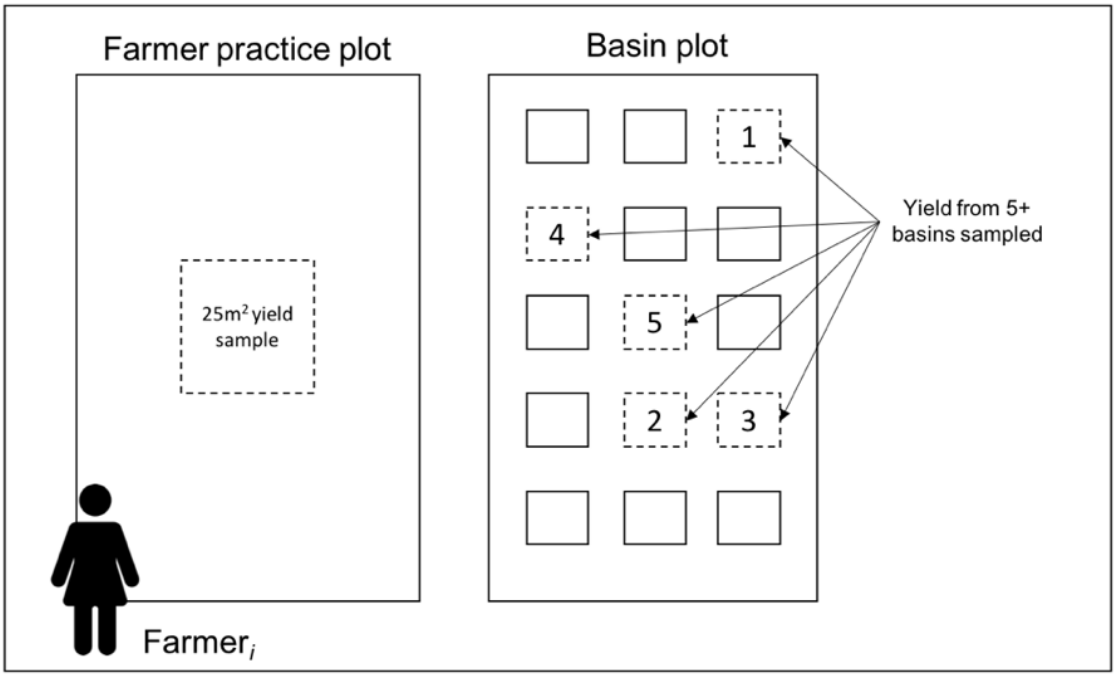

Figure 2.4 Planned comparison sampling design for matched basin and farmer practice plots.

To determine dry grain weight, grain moisture content was derived from a randomly selected sub-set of farms from each sub-county (five farms per sub-county in OND 2018 and 17-41 farms per sub-county in OND 2019[3]). On each farm, a sub-sample of three cobs was taken from each plot, weighed, air-dried for several weeks, shelled, and reweighed. Moisture content results from each sub-county were then averaged and used to convert all other observations from the same sub-county to dry grain

[3] Given the large variation in moisture content between farms in OND 2018 and the greater number of farmers participating in OND 2019, it was decided to increase the number of farms sampled per sub-county.

weight. Yield from each plot was then scaled to yield per hectare. For basin plots, we took the mean dry grain yield of sampled basins and scaled this to yield per hectare using the advised number of basins per hectare (Table 2.3). Basin yields reported in this study are thus potential yield from basins assuming farmers followed the recommended spacing between basins.

Monitoring datasets were then cleaned to only include farms where both a control and at least one treatment plot had been assessed. A total of 29 plots (0.8% of total plots surveyed) with yields greater than 10 t ha^{-1} were excluded as assumed to be unrealistic for rain-fed conditions and treated as errors or extreme outliers. Plots where no maize was harvested were treated as zero yield rather than excluded. Some plots were discarded due to inconsistencies in data collection (e.g., unclear units of measurement, missing plot management information). This resulted in a final cleaned dataset of 3,688 plots (84% of the total plots assessed) from a total of 1,280 individual households (88% of the total households involved in the comparison) (see Table 2.4 for household numbers for each season and site and Table S2.1, Appendix 7 for breakdown of plot numbers by season and site).

Table 2.4 Number of households participating in the planting basin planned comparison each season by project site. Note: Total numbers are not separate households. Of the 1,280 separate households, 376 took part in two or more monitoring seasons.

County	Sub-County	OND 2017	OND 2018	OND 2019	Total
Machakos	Mwala	26	45	78	149
	Yatta	40	25	40	105
Makueni	Mbooni East	55	61	68	184
	Kibwezi East	73	164	112	349
Kitui	Mwingi East	91	160	404	655
	Kitui Rural	139	74	88	301
	All sites	424	529	790	1743

In the final dataset, only 376 households appeared in two or more monitoring seasons. Unfortunately, it is unclear whether this was due to the project's focus on reaching large numbers of farmers and collecting data on newly recruited farmers, to existing farmers dropping out of the planned comparison, or because farmers who had already harvested at the time of survey were not surveyed. Farmer attrition may have introduced biases in our sampling and is a common challenge with conducting multi-seasonal trials (Laajaj et al., 2020). For example, farmers for whom basins worked well may have been more likely to continue with the trial than those for whom basins performed poorly. Similarly, given that farmers who chose to harvest early because of poor crop performance were not surveyed, our sample may be biased towards farms with more favourable growing conditions.

In addition to the OND 2017, 2018 and 2019 monitoring surveys, a household survey was used to collect basic socio-economic data on each farmer and their household when they enrolled with the project (Winowiecki et al., 2019). Of the 1,280 households included in our analysis, 373 households did not take part in the household survey. Only plot-level management data was therefore available for these households.

All surveys were conducted using Open Data Kit Collect, a mobile platform for data collection (Hartung et al., 2010), and administered by trained enumerators who spoke and understood the local language. Feedback workshops were also held with farmers each year to share what project participants had learnt from their planned comparisons with each other, the implementing partners, and the project team and to provide feedback on how to improve project activities.

All data analyses were conducted using R version 4.0.3 (R Core Team, 2020). Yield data analysis focused on within-farm yield difference, that is, the difference in maize grain yield between basin and control plots on the same farm (maize yield on the planting basin plot minus the yield from the plot managed using the farmer's usual tillage practice). Descriptive statistics and cumulative frequency curves were used to examine variability in within-farm yield difference among farms. For OND 2018 and OND 2019 data, several linear mixed models were fitted to explore potential sources of variation in yield response. Explanatory variables covered those associated with plot management and the biophysical and socio-economic context on each farm (Table 2.5). Household, village, and sub-county were included as nested random effects.

In addition to basins dug as part of the planned comparison, many farmers had started to dig additional basins on their farms. To monitor uptake of the basin practice, monitoring surveys included information on the total number of basins on each farm. To assess the potential contribution that these basins had made to household maize self-sufficiency, we estimated the number of additional days of maize each household would have received from their basins compared to if they had planted the equivalent area using their usual farming practice. For each farmer, the number of additional maize days their household was estimated to have received from their basins can be expressed as:

Equation 1.1

$$m_i = \frac{\sum_{j=1}^{s} (y_{ij}\ a_{ij}) - (y_{if}\ a_{ij})}{(h\ c)}$$

Where m_i is the number of additional days of maize farmer i's household received from their basins, s is the number of different basin sizes that farmer i has on their farm, the subscript index j enumerates the types of basins (i.e., 30x30cm, 60x60cm, 90x90cm), y_{ij} is the estimated yield per hectare for basin j on farmer i's farm, a_{ij} is the area of land under basin j, Y_{if} is the estimated yield per hectare for the usual practice used by farmer i, h is the number of members living within the household of farmer, and c is the average daily maize demand per person (220 grams per person per day). Estimated daily maize demand was based on an average suggested calorie intake of 2,231 Kcal per person (regardless of gender and age[4]) derived from the MyPyramid Food Guidance System (Britten et al., 2006), a calorific value of 365 Kcal per 100 grams of maize (USDA, 2021) and maize constituting 36% of an individual's total food calories (Mohajan, 2014).

Lastly, we conducted a profitability analysis. This included estimated gross margins per hectare, returns to labour and value-cost ratios for each basin size and tillage practice, and personal daily income had a household used only basins or only their usual tillage practice on their total cultivated area. Gross margin per hectare from maize production was defined as gross returns minus variable costs, including the cost of family labour[5], and returns to labour was defined as gross margin per hectare divided by required person-days per hectare. Value-cost ratios were obtained by dividing the value of the additional yield from basins by their additional cost compared to the farmer's usual tillage practice. Personal daily income (PDI) was adapted from Harris (2018) and defined as:

Equation 1.2

$$PDI_{ij} = (A_i \ x \ R_i)/(N_i \ \ x \ 365)$$

Where A_i is the area (ha) of farmer i's farm under cultivation, R is the return from maize production for treatment j (i.e., basins or usual practice) on i's farm (\$/ha/year) and N_i is the number of persons in farmer i's household. Gross margins and PDI were reported in both Kenyan Shillings (Ksh) and Purchasing Power Parity (PPP) dollars based on International Comparison Program (ICP) benchmark

[4] Ideally, we would have calculated daily maize demand based on the age and gender of each household member, however, this information was only collected for a small sub-set of households.

[5] While labour costs can be difficult to quantify and valuation likely varies between households, we included imputed labour costs in our profitability analysis. This was based on basins being a labour-intensive practice and a lack of labour being the main reason given by farmers for not increasing the number of basins on their farms (see Table 4.10 in Chapter 4). Furthermore, within our study sites off-farm opportunities do exist (Verkaart et al., 2018) and rural-urban labour migration, particularly of male family members, is common (see Chapters 4 and 5). Thus, setting the opportunity cost of family labour to zero would be inappropriate and likely overstate the attractiveness of basins to smallholder households who rarely rely solely on farming for their livelihoods.

PPP 2017 for household's final consumption expenditure (i.e., 41.64 Ksh per international dollar). With the 2017 PPP, we assume the international poverty line at $2.10 per person per day (Atamanov et al., 2020).

Table 2.5 Explanatory variables included in the linear mixed models on within-farm yield difference.

Variable	Description
Plot management	
Planting basin size	Categorical variable with four levels: i) farmer practice (no basins); ii) 30x30cm basins (small); iii) 60x60cm basins (medium); iv) 90x90cm basins (large).
Farmer's usual tillage practice	Categorical variable with two levels: ox plough or hand hoe cultivation
Maize variety	Categorical variable with two levels: local or improved.
Manure application	Categorical variable with two levels: with and without manure.
Socio-economic context	
Gender of farmer	Boolean variable with two levels: male or female
Age of farmer	Continuous variable.
Marital status of farmer	Categorical variable with two levels: married or unmarried
Primary income Secondary income	Categorical with five levels: i) farming; ii) business; iii) casual employment; iv) formal employment; v) remittances
Land per capita	Continuous variable (ha). Total farm size divide by household size.
Distance to market	Continuous variable (km)
Farmer group membership	Boolean variable with two levels: yes or no
Biophysical context	
Altitude	Continuous variable (m.a.s.l)
In-season rainfall	Continuous variable (mm). Estimated in-season rainfall (total rain falling between 1st October to 31st December) data obtained from CHIRPS (Funk et al., 2015) for all households based on their GPS location.
Erosion status	Whether the farmer experiences erosion problems on their farm (self-reported). Categorical variable with two levels: yes or no.
Soil quality ranking	Farmer's description of soil quality on their farm. Categorical variable with three levels: i) high (good yields can be obtained without adding organic/inorganic fertilizer); ii) medium (yields can be maximized with organic/inorganic fertilizer but fair yields can be obtained without); iii) low (very little can grow without significant addition of organic/inorganic fertilizer).

3. Results

Here, we present our various analyses, moving with increasing complexity from the plot-scale to the farm and household scale. Along the way, we reflect on some of our analytical decisions and discuss the challenges and merits of the various approaches applied.

3.1 Maize yields and yield response

Based on overall average yield, planting basins performed much better than farmers' usual tillage systems (Table 2.6 and Figure 2.5). Across seasons, plots with basins had median[6] yields ranging from 0.52 to 5.54 t ha^{-1} higher than those without, the majority of these differences in median yield being significant. Yet, the size of this effect differed between monitoring seasons and with basin size. The smallest differences in average yield were seen in OND 2017 – the season receiving the least rainfall – and the largest differences in average yield were seen in OND 2019 – the season receiving the most rainfall. In OND 2017 and 2018, the smallest basin size had the smallest average yield effect. Subsequently, we saw a decrease in the number of small basins assessed each season, reflecting farmers decision to drop this option from their on-farm trials following its poor performance. The medium sized basins provided slightly higher median yields compared to the largest size of basin in all seasons except OND 2019. In OND 2017, the season experiencing widespread drought, we also see a far larger proportion of farmer practice plots reported to have experienced complete crop failure (defined here as maize yields under 0.05 t ha^{-1}) (Table 2.8). This likely reflects the role of basins in increasing water availability to plants and bridging intra-seasonal dry spells during germination and establishment.

[6] Throughout this chapter, we primarily refer to the median rather than the mean. This is because the median is less affected by extreme values and skewed data distributions – characteristics typical of yield data collected from large on-farm trials.

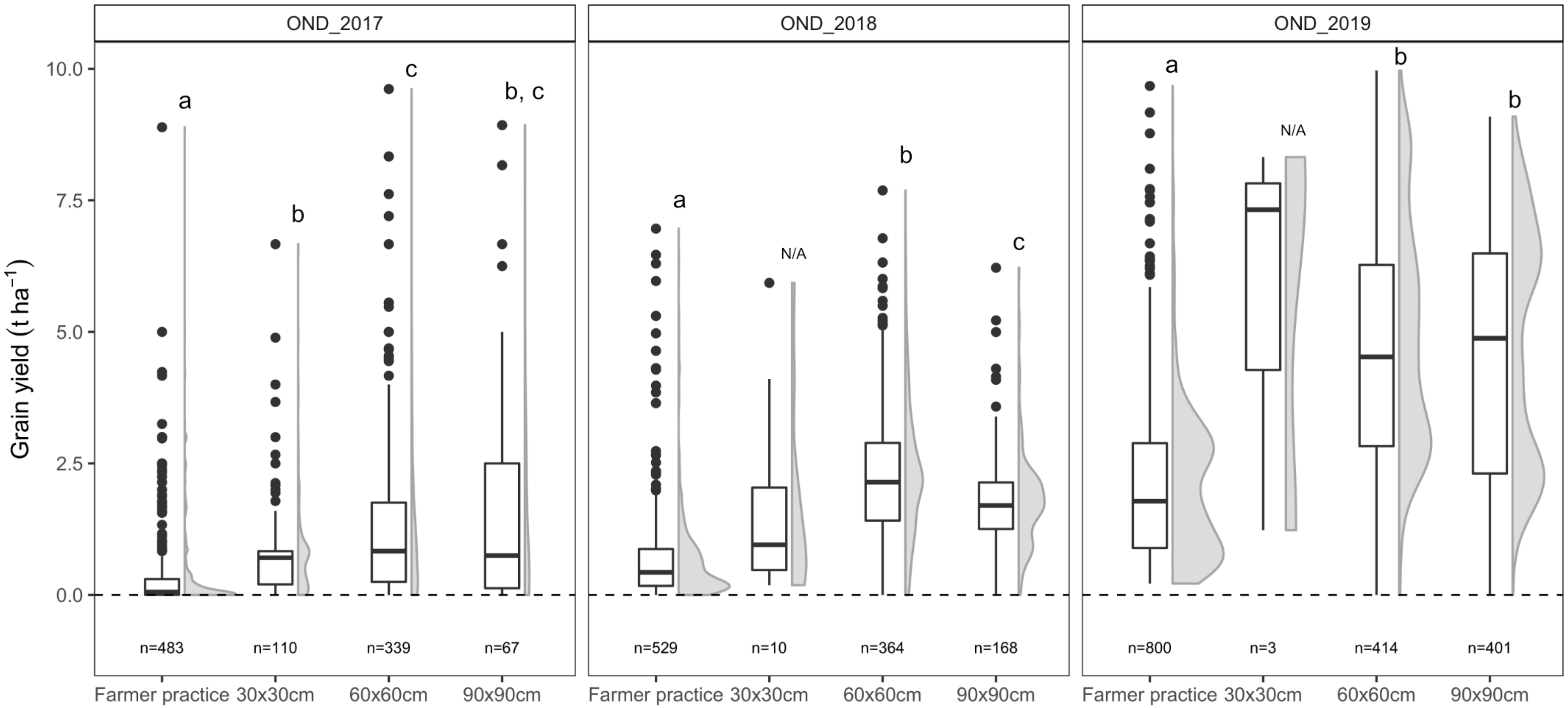

Figure 2.5 Maize yield (t ha^{-1}) for different sizes of planting basin and farmers' usual tillage practice during each Oct-Nov-Dec (OND) monitoring season. For each season, different superscript letters are significantly different ($p < 0.05$) based on pairwise Wilcoxon Rank Sum test. Small basins (30x30cm) were excluded from statistical analyses for 2018 and 2019 due to low numbers of observations. Across all seasons, median yields were higher for planting basins compared to farmers' usual practice but showed greater variation in performance.

Table 2.6 Average maize yields from different sized basins and farmers' usual tillage practice for each monitoring season.

	Yield (t ha^{-1})														
	OND 2017[1]					**OND 2018**					**OND 2019**				
	N	**Median**	**Mean**	**SD**	**P-value**[2] **(*r*)**	**N**	**Median**	**Mean**	**SD**	**P-value**[2] **(*r*)**	**N**	**Median**	**Mean**	**SD**	**P-value**[2] **(*r*)**
Farmer practice	483	0.06	0.37	0.81	---	529	0.43	0.71	0.95	---	800	1.78	2.06	1.44	---
30x30cm basins	110	0.71	0.82	1.01	**0.00 (-0.21)**	10	0.95	1.74	1.89	**0.01 (-0.62)**	3	7.32	5.62	3.84	---
60x60cm basins	339	0.83	1.32	1.52	**0.00 (-0.52)**	364	2.14	2.28	1.29	**0.00 (-0.56)**	413	4.52	4.82	2.14	**0.00 (-0.55)**
90x90cm basins	67	0.75	1.57	2.01	**0.00 (-0.47)**	168	1.70	1.79	0.90	**0.00 (-0.58)**	400	4.93	4.76	2.24	**0.00 (-0.60)**

[1] Yields for OND 2017 are based on farmer estimated yield, not measured.
[2] Wilcoxon signed rank test of whether the median is different from the paired farmer practice plots. Significance: <0.05 in bold (Pearson's correlation coefficient).

Table 2.7 Average within-farm yield differences for paired treatment-control plots by basin size and monitoring season.

	Within-farm yield difference (t ha^{-1})														
	OND 2017[1]					**OND 2018**					**OND 2019**				
	N	**Median**	**Mean**	**SD**	**P-value**[2] **(*r*)**	**N**	**Median**	**Mean**	**SD**	**P-value**[2] **(*r*)**	**N**	**Median**	**Mean**	**SD**	**P-value**[2] **(*r*)**
30x30cm basins	110	0.19	0.33	1.20	**0.00 (-0.30)**	10	0.69	1.13	0.40	**0.01 (-0.87)**	3	2.22	1.38	1.76	---
60x60cm basins	339	0.68	1.06	1.42	**0.00 (-0.74)**	364	1.57	1.47	1.24	**0.00 (-0.79)**	413	2.43	2.43	2.02	**0.00 (-0.78)**
90x90cm basins	67	0.38	1.27	2.02	**0.00 (-0.67)**	168	1.47	1.32	0.90	**0.00 (-0.82)**	400	2.76	3.07	1.82	**0.00 (-0.85)**

[1] Yields for OND 2017 are based on farmer estimated yield, not measured.
[2] Wilcoxon signed rank test of whether the median is different from zero. Significance: <0.05 in bold. (Pearson's correlation coefficient).

Table 2.8 Prevalence of crop failure (i.e., yield less than 0.05 t ha^{-1}) for plots with and without planting basins.

	Farmers usual practice	**Planting basins**	***p*-value[1]**
OND 2017 (n = 999)	30% (236/483)	11% (76/516)	<0.000
OND 2018 (n = 1071)	5% (25/529)	3% (14/542)	0.073
OND 2019 (n = 1618)	0% (0/800)	0.2% (2/818)	0.500
All seasons (n = 3688)	14% (261/1812)	5% (92/1876)	<0.000

[1] Fisher's exact test (two-sided)

Within-farm yield differences (Table 2.7) reveal a similar picture to the differences in overall average yield (Table 2.6) but reflect the effect of basins as experienced by each farmer (i.e., treatment yield minus control yield for matched on-farm plots). Plotting cumulative frequency curves of these within-farm differences (Figure 2.6) showed that while the average overall basin yields and yield increments (Table 2.6 and 2.8) are large and positive, they hide considerable variation in the size of treatment effect among farmers. Visualising the cumulative distribution of within-farm differences (as done in Figure 2.6) illustrates the potential risk posed to farmers when basins are adopted as a generalised recommendation (see Figure 2.7 for guidance on interpreting cumulative frequency curves and inferring risk).

Taking a similar approach to Laajaj et al. (2020) we overlaid these cumulative distribution plots with lines marking the estimated within-farm yield difference needed to achieve various value-cost ratios (i.e., the value of additional yield from basins divided by the additional cost of their implementation). These values were derived from our profitability analysis in section 3.4 of this chapter. In Figure 2.6 the first vertical line (solid) depicts where the yield difference is zero. The second line (dashed) marks the median estimated yield difference needed for a value-cost ratio of 1:1 (i.e., the break-even point, beyond which profits turn positive) and the third line (dashed) the median yield difference required for a value-cost ratio of 2:1 (i.e., the point at which profit is equal to 100% of the cost) – a threshold commonly used by agronomists to determine whether an innovation is likely to be adopted (Laajaj et al., 2020).

While most farmers experienced yield increases from their basins, a sizable proportion of basin plots in OND 2017 and OND 2018 are unlikely to have achieved a value-cost ratio greater than one (67% and 35% in OND 2017 and 2018, respectively), and only a minority are likely to have achieved a value-cost ratio greater than 2:1 (16% and 23% in OND 2017 and 2018, respectively). Furthermore, in OND 2017, 23% of basin plots had either a negative or no effect on yield compared to only 9% and 6% of basin plots in OND 2018 and OND 2019, respectively. In contrast to OND 2017 and 2018, 87% of basin plots in OND 2019 are estimated to have achieved a value-cost ratio greater than one and 56% greater than a 2:1 ratio. Interestingly, whilst OND 2019 had a higher average yield difference compared to the other monitoring seasons (curve is located further to the right) we also saw greater variation in this response (curve is less vertical). A potential explanation could be the greater variation in within-season rainfall seen in OND 2019 (Figure 2.3).

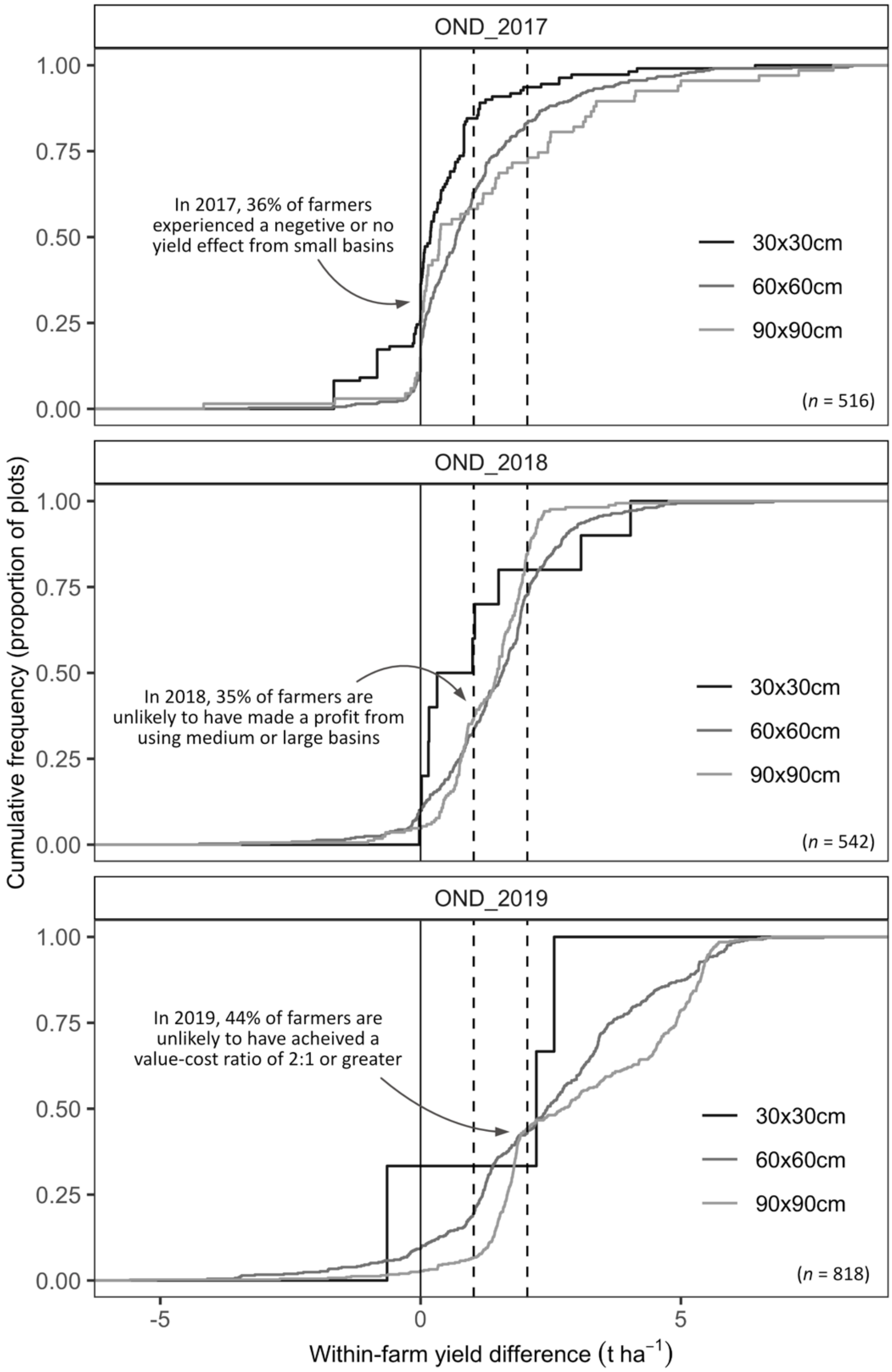

Figure 2.6 Cumulative frequency curves showing the distribution of within-farm yield difference for different sizes of basin and each monitoring season. Curves show the cumulative proportion of farmers (y axis) that experienced a given yield difference or less (x axis). See Figure 2.7 for further guidance on interpreting cumulative frequency curves. Vertical lines, working from left to right, show where the yield difference is zero (solid), the median yield difference needed for a value-cost ratio of 1:1 (i.e., the break-even point, beyond which profits turn positive), and the median yield difference required for a value-cost ratio of 2:1 (i.e., the point at which profit is equal to 100% of the cost). The values for a 1:1 and 2:1 value-cost ratio is 1.02 and 2.05 t ha^{-1}, respectively, and were derived from our profitability analysis in section 3.4 of this chapter.

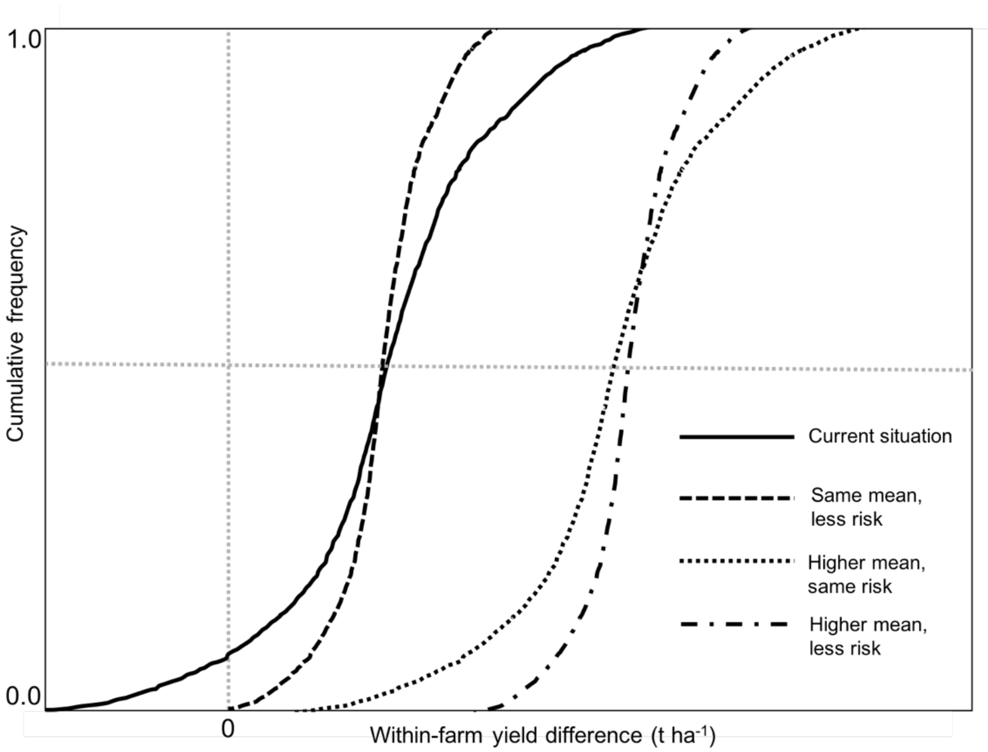

Figure 2.7 Guidance on interpreting cumulative frequency curves. Figure and caption adapted from Vanlauwe, Coe and Giller (2019). Risk of a negative effect on yield can be reduced by shifting the cumulative frequency curve to the right or making it straighter along its vertical axis, or both. The horizontal line (dashed) shows where the curves intersect the mean yield increase on the x-axis. The vertical line (dashed) shows where the yield difference turns positive. As argued by Coe and colleagues, the goal of researchers should be to better understand the variation in treatment effect, and to straighten and shift the curve right, thus reducing risk farmers face when adopting new innovations.

While average maize yield from basins in this study are high compared to the national average for Kenya, they are within the expected range for rain-fed conditions. National average maize yield in Kenya oscillates around 1.9 t ha^{-1} while the yield potential under rain-fed conditions is estimated at 7.9 t ha^{-1} (GYGWPA, 2021). Our results are also comparable to other studies assessing maize yield from basins (Figure 2.8). However, it is worth considering that yields from labour-intensive practices such as basins may be exaggerated when yields from small experimental plots are scaled to yield per hectare. As later discussed, the majority of farmers had very few basins on their farms and these basins were often located close to the home. These basins likely received greater care and attention from farmers than maize grown under farmers' usual tillage practices. Given the limits to household labour and labour-intensive nature of basins, such care is unlikely to scale to larger numbers of basins (the estimated number of medium sized basins per hectare is 6,944 basins).

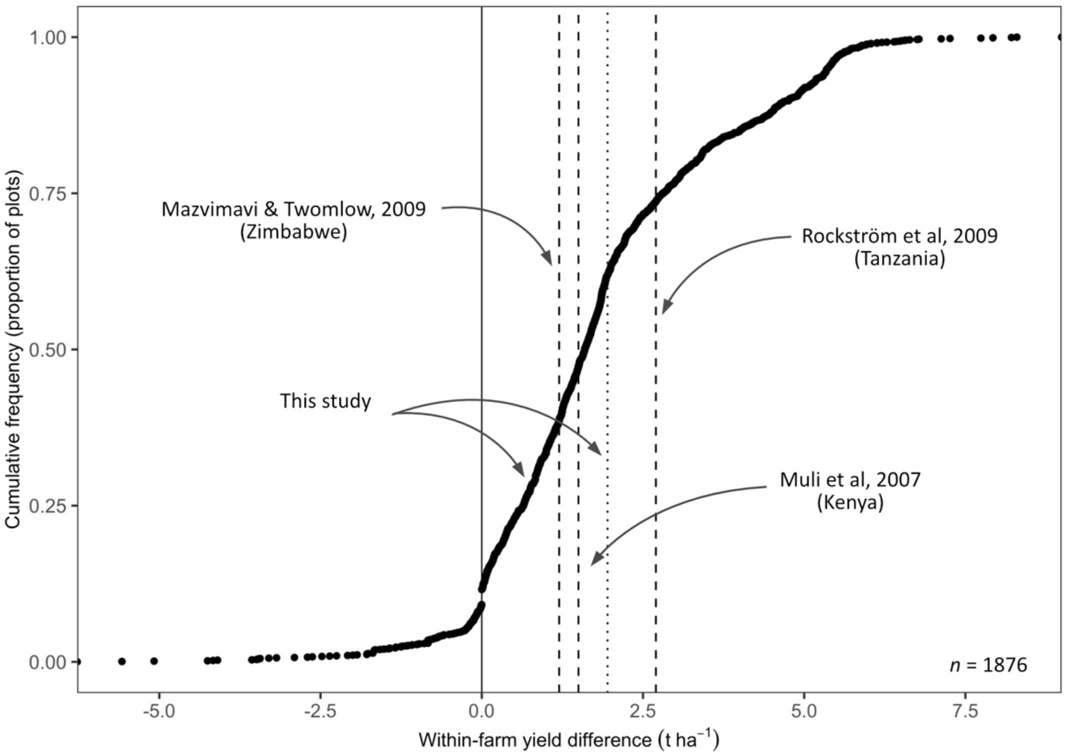

Figure 2.8 Cumulative frequency curve showing the distribution of within-farm maize yield differences and mean yield difference from this study (curve and dotted line) compared to reported average yield effects from other studies on the efficacy of planting basins (dashed lines).

3.2 Exploring variation in yield response

It is expected that understanding the sources of variation in treatment effect from agricultural innovations will lead to better tailored recommendations with more reliable outcomes, and thus reduced risk to farmers (Coe et al., 2016; Vanlauwe et al., 2019). To explore the variation in within-farm yield difference we fitted several linear mixed models[7] using data from OND 2018 and OND 2019[8] for medium and large basins only[9] (see S2.1 to S2.4, Appendix 7 for model diagnostics). Since household characteristics were only collected for a subset of farmers (Table 2.9), we first modelled yield difference for all observations (n = 1,345) using plot management and biophysical covariates

[7] Linear mixed models were chosen over simple linear models due to the nested hierarchical structure of our data (i.e., farmers within villages, within sub-counties), and thus non-independence between observations. Given the groupings within our data, it is reasonable to expect, for example, that individual observations within sites would be more similar than observations from different sites. To account for the variance explained by project site, village and household, these factors were included as random effects (with random intercepts) rather than fixed effects.
[8] Observations from OND 2017 were excluded from the analysis since, unlike OND 2018 and OND 2019 data, they are based on farmer estimated yields rather than measured yields.
[9] Observation for small basins were excluded given the low numbers assessed in OND 2018 and OND 2019.

as fixed effects (Model 1, Table 2.10), and then again for the subset of observations for which we had household-level data ($n = 965$) using the full set of plot management, biophysical and socio-economic covariates as fixed effects (Model 2, Table 2.10). In both models, nested random effects included household, village, and project site (i.e., sub-county) with random intercepts.

Across the two models, consistent effects for in-season rainfall, altitude and manure application suggest that basins performed best when combined with manure, under higher rainfall conditions and at higher altitudes. Model 1 indicated that basin size also mattered, with large basins associated with smaller yield differences. However, while significant, the sizes of these effects were small and, all together, our fixed factors explained only 13% and 14% of the total variation explained by models 1 and 2, respectively. In contrast, 44% and 50% of variation was attributed to our random effects, largely driven by project site (Table 2.11). This suggests that missing explanatory factors likely vary at the sub-county level.

Since none of the socio-economic factors included in model 2 showed a strong association with yield difference, we proceed with exploring variation in yield difference for each basin size using the full set of observations and plot management and biophysical covariates only (Model 3 and 4, Table 2.12 and Table 2.13). At this stage, household was also removed as a random effect as few households had multiple plots of the same size of basin. Once again, across models a consistent effect of rainfall was seen, suggesting both medium and large basins performed best with increasing rainfall (Figure 2.9). The two models also indicate that the use of local maize varieties with medium basins was associated with smaller yield differences, but less so for the large basins, and that manure application and altitude were associated with larger yield differences when combined with the large basins, but not the medium sized basins (see Figures S2.1 and S2.2, Appendix 7). Nevertheless, once again, effect sizes were small and the proportion of total variation explained by fixed effects for models 3 and 4 (10% and 21%, respectively) was considerably less than the proportion explained by our random effects (42% and 38%, respectively), in particular, project site.

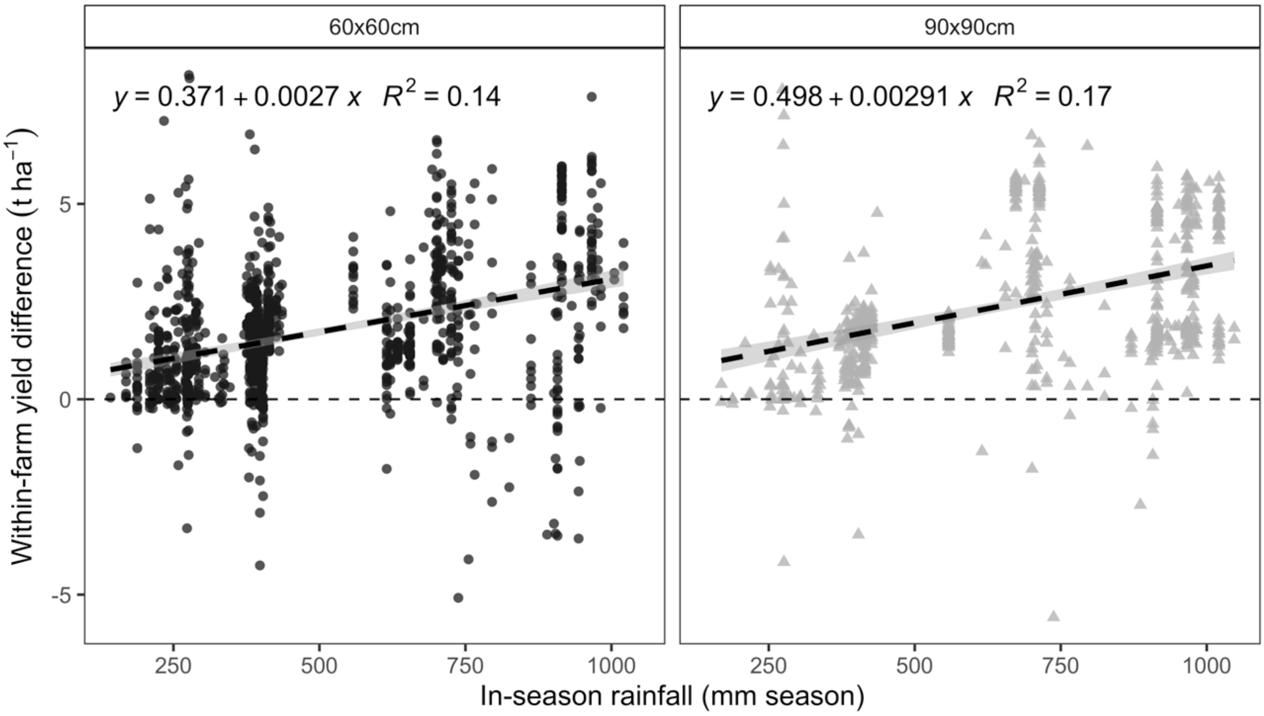

Figure 2.9 Within-farm yield difference (t ha^{-1}) from medium (60x60cm) and large (90x90cm) basins regressed against within-season rainfall. Within-farm yield difference showed a positive but weak correlation with in-season rainfall for both medium (60x60cm) and large (90x90cm) basins.

Taking a closer look at yield difference by sub-county (Figure 2.10 and 2.11), we see large variation in average yield effect and response across the six sites. For example, farmers in Mwingi East (Kitui County) experienced large yield gains from their basins, while many farmers in Mwala (Machakos County) saw poor results. Unfortunately, knowing that yield response varies between sites provides little insight into what might happen in other locations (i.e., what is it about the difference between sites?).

Table 2.9 Summary of household level and socio-economic characteristics collected for a subset of 907 households. (Missing information for 373 households in 2019 because they were new farmers and not included in the farmer profiling survey).

	Machakos County		**Makueni County**		**Kitui County**		**All sites (n = 907)**
	Mwala (n = 71)	**Yatta (n = 56)**	**Kibwezi East (n = 191)**	**Mbooni East (n = 111)**	**Mwingi East (n = 300)**	**Kitui Rural (n = 178)**	
Farmer gender (female)	66% (47)	80% (45)	74% (151)	75% (83)	74% (222)	84% (149)	77% (697)
Farmer age	48.4 (11.5)	52.5 (13.3)	44.3 (12.6)	46.2 (11.0)	45.1 (13.0)	46.1 (13.7)	46.0 (12.9)
Marital status (married)	90% (64)	79% (44)	89% (170)	80% (89)	88% (263)	88% (157)	86% (787)
Household size	5.1 (3.0)	6.2 (2.6)	5.5 (1.7)	6.4 (3.8)	6.2 (2.5)	6.1 (2.5)	6.0 (2.6)
Farm size (ha)	2.4 (1.4)	1.8 (1.3)	3.9 (5.6)	5.0 (6.6)	4.2 (2.4)	1.8 (1.3)	3.5 (4.0)
Primary income (farming)	96% (68)	66% (37)	80% (153)	68% (76)	79% (237)	95% (169)	82% (740)
Secondary income (farming)	75% (52)	59% (33)	40% (75)	54% (60)	70% (204)	37% (66)	55% (490)
Distance from market (km)	5.3 (3.3)	5.8 (4.7)	8.0 (6.4)	3.3 (2.8)	10.4 (5.1)	4.8 (2.7)	7.3 (5.4)
Farmer group member (% yes)	32% (23)	23% (13)	55% (106)	16% (18)	27% (82)	3% (6)	27% (248)
Hand hoe cultivation (% yes)	17% (12)	21% (12)	30% (58)	5% (6)	42% (125)	19% (34)	27% (247)
Soil quality (% low)	31% (22)	30% (17)	19% (36)	17% (19)	26% (78)	19% (34)	23% (206)
Soil quality (% medium)	54% (38)	55% (31)	72% (137)	79% (88)	51% (153)	74% (131)	64% (578)
Soil quality (% high)	15% (11)	14% (8)	9% (18)	4% (4)	23% (69)	7% (13)	14% (123)
Erosion (% yes)	54% (38)	61% (34)	84% (156)	86% (95)	65% (195)	60% (107)	69% (627)
Altitude (m.a.s.l)	1236.4 (376.9)	1162.1 (165.2)	815.6 (122.7)	978.5 (105.8)	996.1 (204.6)	942.0 (67.3)	974.4 (212.3)

Statistics presented: % (n); Mean (SD)

Table 2.10 Linear mixed model parameters for within-farm yield difference. Because some farmers did not take part in the household survey, Model 1 uses all observations and biophysical and plot management covariates, while Model 2 uses the subset of observations for which we have household socio-economic data. For both models, nested random effects include household, village and project site with random intercepts. Similar to R^2 for simple linear models, marginal R^2 and conditional R^2 provide intuitive metrics for comparing the fit of linear mixed models (Nakagawa and Schielzeth, 2013). Marginal R describes the proportion of total variance explained by the fixed effects, while conditional R^2 describes the proportion explained by both fixed and random effects.

	Model 1 (with all observations)				Model 2 (with subset)			
	B	***SE***	***CI***	***P****	***B***	***SE***	***CI***	***P****
Basin plot management								
Tillage: medium basins (omitted)	---	---	---	---	---	---	---	---
Tillage: large basins	-0.358	0.0968	-0.55/-0.17	**<0.000**	-0.205	0.108	-0.41/0.01	0.059
Manure: no	-0.412	0.092	-0.59/-0.23	**<0.000**	-0.240	0.102	-0.44/-0.05	**0.019**
Maize variety: local	-0.142	0.129	-0.39/0.11	0.269	-0.269	0.145	-0.55/0.01	0.063
Farmer practice: ox plough	-0.074	0.114	-0.30/0.15	0.518	-0.146	0.129	-0.40/0.11	0.261
Biophysical context								
Season: OND 2018 (omitted)	---	---	---	---	---	---	---	---
Season: OND 2019	0.135	0.204	-0.27/0.54	0.508	0.333	0.257	-0.17-0.84	0.197
In-season rainfall (scaled)	0.517	0.100	0.32/0.71	**<0.000**	0.340	0.131	0.08-0.60	**0.010**
Altitude (scaled)	0.338	0.063	0.21/0.46	**<0.000**	0.329	0.066	0.19-0.46	**<0.000**
Soil quality: high (omitted)	---	---	---	---	---	---	---	---
Soil quality: medium	---	---	---	---	0.236	0.139	-0.04/0.51	0.090
Soil quality: low	---	---	---	---	0.166	0.161	-0.15/0.48	0.304
Erosion on farm: yes	---	---	---	---	-0.144	0.102	-0.34/0.06	0.160
Socio-economic context								
Land per capita (scaled)	---	---	---	---	0.004	0.047	-0.09/0.10	0.928
Distance from market (scaled)	---	---	---	---	-0.010	0.060	-0.12/0.11	0.869
Primary income: farming	---	---	---	---	0.149	0.126	-0.10/0.40	0.238
Secondary income: farming	---	---	---	---	0.087	0.099	-0.11/0.28	0.380
Farmer age (scaled)	---	---	---	---	-0.015	0.047	-0.11/0.08	0.756
Farmer gender: male	---	---	---	---	0.058	0.109	-0.16/0.27	0.596
Marital status: unmarried	---	---	---	---	0.064	0.135	-0.20/0.33	0.635
Member of farmer group: yes	---	---	---	---	0.024	0.111	-0.19/0.24	0.827
N	1345				956			
Constant	2.224				1.679			
**Marginal R^2 ** **	0.13				0.14			
**Conditional R^2 ** **	0.63				0.58			

** P-values estimated via t-tests using the Satterthwaite approximations to degrees of freedom.*
*** Marginal and conditional R-squared statistics based on Nakagawa and Schielzeth et al., 2017.*

Table 2.11 Random effects for model 1 and 2 in Table 2.10.

Random effects	Model 1 (with all observations)				Model 2 (with subset)			
	Variance	***SD***	***AIC***	***Pr ($<\chi^2$)***	***Variance***	***SD***	***AIC***	***Pr ($<\chi^2$)***
Household: village: project site	0.304	0.551	4828.7	**0.005**	0.189	0.435	3348.4	**0.034**
Village: project site	0.338	0.582	4860.0	**<0.000**	0.185	0.430	3377.9	**<0.000**
Project site	1.522	1.234	4901.8	**<0.000**	1.129	1.063	3393.8	**<0.000**
Residual	1.597	1.264	---	---	1.474	1.214	---	---

Table 2.12 Linear mixed model parameters for within-farm yield difference. Model 3 uses observation from medium sized basins only and model 4 observation from large basins only. Both use the biophysical and plot management covariates as fixed effects only. Nested random effects included household and village with random intercepts. Marginal R describes the proportion of total variance explained by the fixed effects, while conditional R^2 describes the proportion explained by both fixed and random effects.

	Model 3 (medium basins)				Model 4 (large basins)			
	B	***SE***	***CI***	***P****	***B***	***SE***	***CI***	***P****
Basin plot management								
Manure: no	-0.054	0.118	-0.28/0.18	0.648	-0.748	0.143	-1.03/-0.47	**<0.000**
Maize variety: local	-0.371	0.154	-0.67/-0.07	**0.016**	0.403	0.225	-0.04/0.84	0.073
Farmer practice: ox plough	0.155	0.165	-0.17/0.48	0.347	-0.267	0.153	-0.57/0.3	0.081
Biophysical context								
Season: OND 2018 (omitted)	---	---	---	---	---	---	---	---
Season: OND 2019	-0.145	0.289	-0.71/0.42	0.615	0.014	0.334	-0.64/0.67	0.966
In-season rainfall (scaled)	0.670	0.151	0.37/0.97	**<0.000**	0.602	0.145	0.32/0.89	**<0.000**
Altitude (scaled)	-0.050	0.084	-0.21/0.11	0.549	0.573	0.094	0.39/0.76	**<0.000**
N	777				568			
Constant	2.035				2.262			
Marginal R^2 **	0.10				0.21			
Conditional R^2 **	0.52				0.59			

** P-values estimated via t-tests using the Satterthwaite approximations to degrees of freedom.*
*** Marginal and conditional R-squared statistics based on Nakagawa and Schielzeth et al., 2017.*

Table 2.13 Random effects for model 3 and 4 in Table 2.12.

Random effects	Model 3 (medium basins)				Model 4 (large basins)			
	Variance	***SD***	***AIC***	***Pr ($<\chi^2$)***	***Variance***	***SD***	***AIC***	***Pr ($<\chi^2$)***
Village: project site	0.308	0.555	2810.8	**<0.000**	0.297	0.545	2025.1	**<0.000**
Project site	1.294	1.137	2858.6	**<0.000**	1.300	1.140	2035.2	**<0.000**
Residual	1.843	1.358	---	---	1.757	1.326	---	---

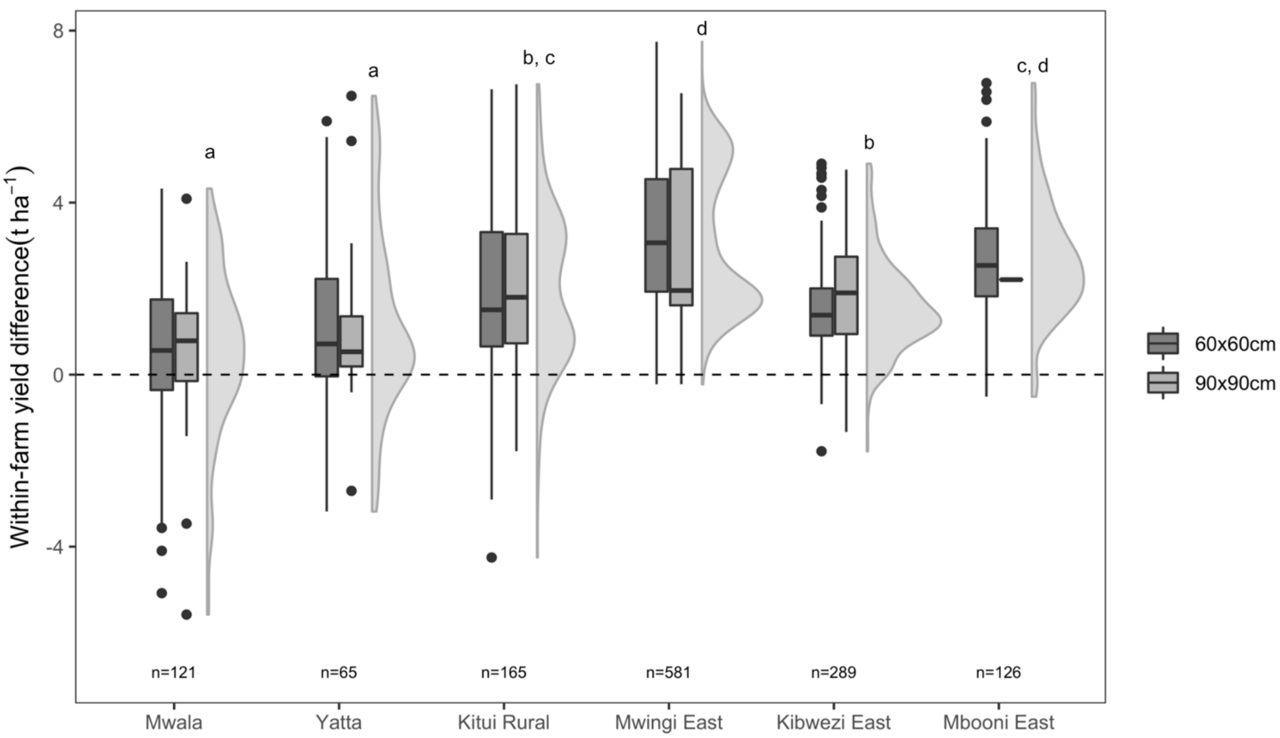

Figure 2.10 Within-farm yield difference for medium (60x60cm) and large (90x90cm) basins by sub-county. Note: different superscript letters are significantly different ($p < 0.05$) based on pairwise Wilcoxon Rank Sum test. Statistical test uses observations from both medium (60x60cm) and large basins (90x90cm). On average, planting basins performed best in Mwala (Machakos County) and the least in Mwingi East (Kitui County).

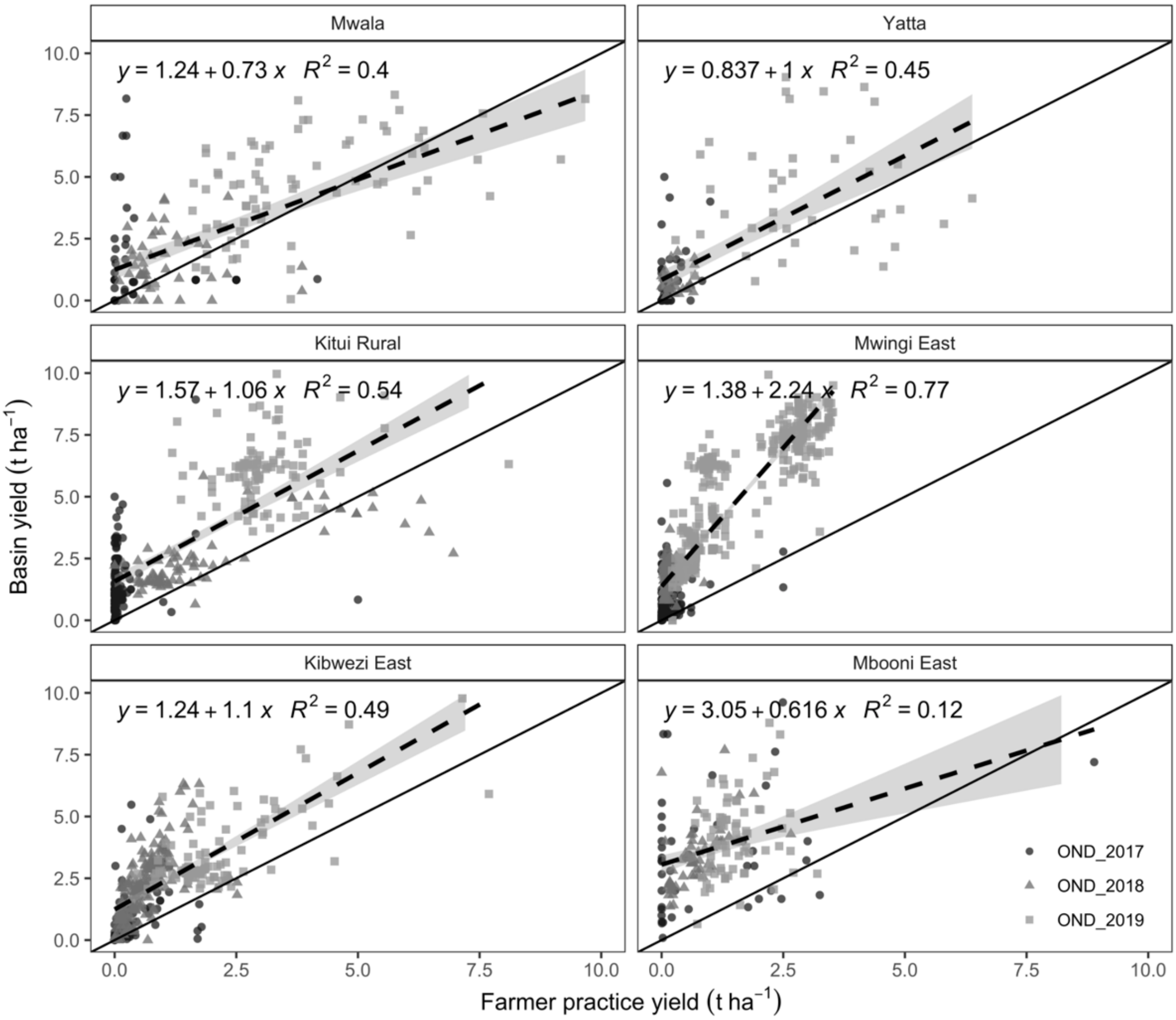

Figure 2.11 Maize yield from basin plots regressed against yield from paired farmer practice plots by sub-county. Data points falling above solid intercept line indicate a positive yield response, those falling below indicate a negative yield response. Assuming yield from farmers' usual practice can be used as a proxy for growing conditions, basins in Mwingi East had a greater yield effect under more favourable growing conditions. In contrast, basins in Mwala had a lesser effect under more favourable growing conditions, highlighting the variable performance of basins across sub-counties.

The large amounts of noise and unexplained variation in yield effect are also likely due to the nature of large on-farm participatory trials and variation in how individual farmers had implemented and managed their basins. This variation can be seen in our survey data that shows farmyard manure and improved maize varieties were used in a higher proportion of plots with basins compared to paired farmer practice plots (Table 2.14).

Table 2.14 Proportion of basin and farmer practice plots with manure and improved maize varieties.

	Farmer practice plots	Planting basin plots	*p*-value[1]
Manure applied			
OND 2017 (n = 999)	78% (377/483)	69% (358/516)	0.002
OND 2018 (n = 1071)	16% (84/529)	40% (218/542)	<0.000
OND 2019 (n = 1618)	9% (74/800)	43% (353/818)	<0.000
All seasons (n = 3688)	30% (535/1812)	50% (929/1876)	<0.000
Improved maize variety			
OND 2017 (n = 999)	18% (87/483)	30% (153/516)	<0.000
OND 2018 (n = 1071)	19% (101/529)	27% (149/542)	0.001
OND 2019 (n = 1618)	11% (86/800)	16% (131/818)	0.002
All seasons (n = 3688)	15% (274/1812)	23% (433/1876)	<0.000

Statistics presented: % (count)
[1]Fisher's exact test (two-sided)

This difference in management is particularly pronounced for the application of manure. Despite the majority of both basin and farmer practice plots being manured in OND 2017, only 12% of farmer practice plots received manure during the following seasons, compared to 42% of basin plots. This likely reflects that although farmers may have adhered to the PC protocol during the first season (e.g., comparing manured treatment plots with manured control plots), in following seasons they were no longer willing to invest time and resources adding manure to farmer practice plots – plots which yielded poor returns compared to those with basins.

Field observations made during farm visits and workshops illustrated the various ways in which farmers had innovated in their implementation and management of the basin practice (Figure 2.12). Many farmers had located their basins close to their home compound. Others were seen using supplementary irrigation in combination with their basins. Many had opted to use an alternative spacing between basins to those prescribed in the PC protocol. Others had combined basins with additional soil and water conservation structures such as ridges (created using the spoil from basin excavation). In OND 2019, some farmers modified their basins in response to the heavy rains so as to avoid waterlogging and depressed yields. These management adaptations included removing excess water, diverting run-off from entering the basins using additional trenches and refilling the basins with soil. Outside of the planned comparison, farmers had also started using basins for growing crops other than maize, such as squash, coriander and kale. One farmer had lined several basins with black plastic to conserve water and had, much to the surprise of her family members, successfully grown arrowroot (*Maranta arundinacea*) – a starchy root vegetable requiring damp conditions.

Regrettably, our monitoring surveys failed to capture many of these adaptations and variations in plot management.

Figure 2.12 Examples of farmer adaptations of the basin practice and management, including (from top left to bottom right) use of basins for growing kale, lining basins with plastic to grow arrowroot, growing coriander, combining basins with other soil and water conservation structures such as ridges, and using supplementary irrigation.

3.3 Days of maize self-provision

In order to translate yield differences from basins into the specific benefit households and their members received, we first estimated the number of additional days of maize each household received from the total number of basins on their farm (Equation 1.2, Table 2.15, see Table S2.3, Appendix 7 for breakdown by sub-county).

Farmers were estimated to have received relatively few additional days of maize from their basins in OND 2017 and OND 2018 (a median of two days and four days, respectively). However, in OND 2019, the median number of additional days farmers are estimated to have received is far higher (18 days) but, once again, we see large variation between farms (Figure 2.13). These results suggest that for many households, yield increases from basins did not necessarily translate into substantial increases in maize self-provision – at least, not at the current levels of uptake among farmers.

While a handful of farmers had invested heavily in basins and had over 2,000 basins on their farms, the vast majority had relatively low numbers of basins (Table 2.15 – see Table S2.3, Appendix 7 for breakdown by sub-county). Furthermore, for farmers who were monitored for two or more seasons the average area of basins on their farm remained low and relatively stable between seasons (Figure 2.14) – bar a few exceptions.

Assuming a difference of 30 days of maize self-provision as being large enough to make a meaningful contribution to household food security, we then calculated (for farmers who had tested the medium (60x60cm) basins and received a positive yield response) the number of medium basins each household would have needed to achieve an extra month's worth of gain (Table 2.15). The number of medium basins needed was far higher than what farmers had on their farms. Over the three seasons the median number of basins per farm was 30 basins while the median number of medium basins required for an additional 30 days of maize was 216 basins.

Table 2.15 Number/area of basins per farm, additional days of maize household received from their current basins, and, for those who tested the 60x60cm basins and received a positive yield response, the estimated number/area of 60x60cm basins required to have achieved an additional 30-days of maize for their family.

	Current number of basins on farm (all sizes)	Area of farm currently under basins (m^2)	Additional days of maize from current basins	Number of medium basins needed for additional 30-days of maize (for households who experienced positive effect from medium basins)		
				Number of basins	**Area (m^2)**	**% of cultivated area**
OND 2017	30 (20, 70)	43.20 (28.80, 103.68)	2 (0, 7)	275 (132, 638)	396.00 (189.41, 919.33)	3.06 (1.33, 7.63)
OND 2018	21 (10, 50)	36.00 (20.16, 76.45)	4 (1, 10)	154 (99, 264)	221.63 (141.97, 379.79)	1.23 (0.69, 2.81)
OND 2019	49 (24, 80)	81.00 (45.00, 146.2)	18 (6, 34)	97 (63, 184)	139.37 (91.07, 264.84)	0.83 (0.43, 1.85)

Statistics presented: Median (IQR)

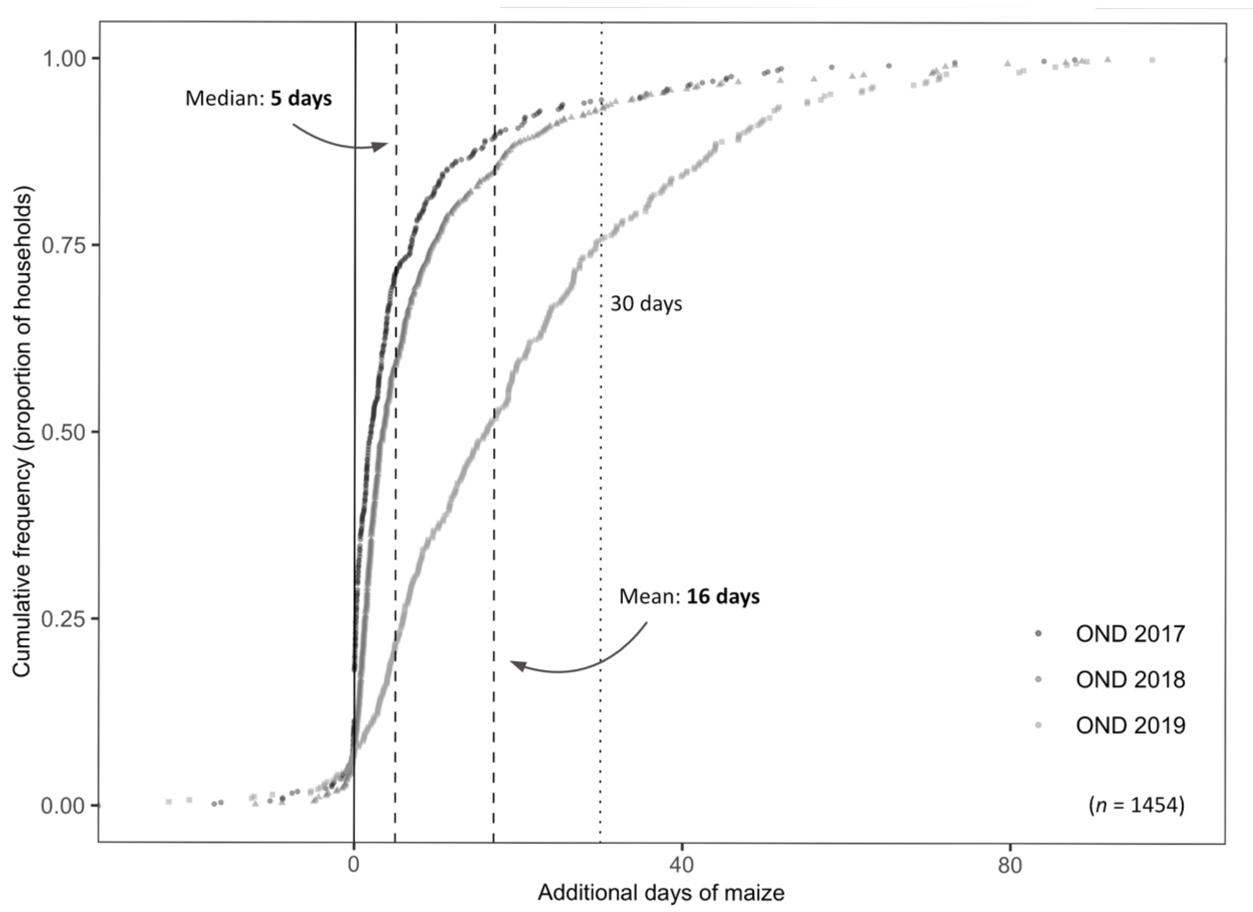

Figure 2.13 Cumulative distribution curves showing the number of additional days of maize self-provision households are estimated to have received from the total number of basins on their farm in each monitoring season. Vertical lines show mean and median additional maize days that households are estimated to have received (dashed). 30 days of additional maize (dotted) shown for reference.

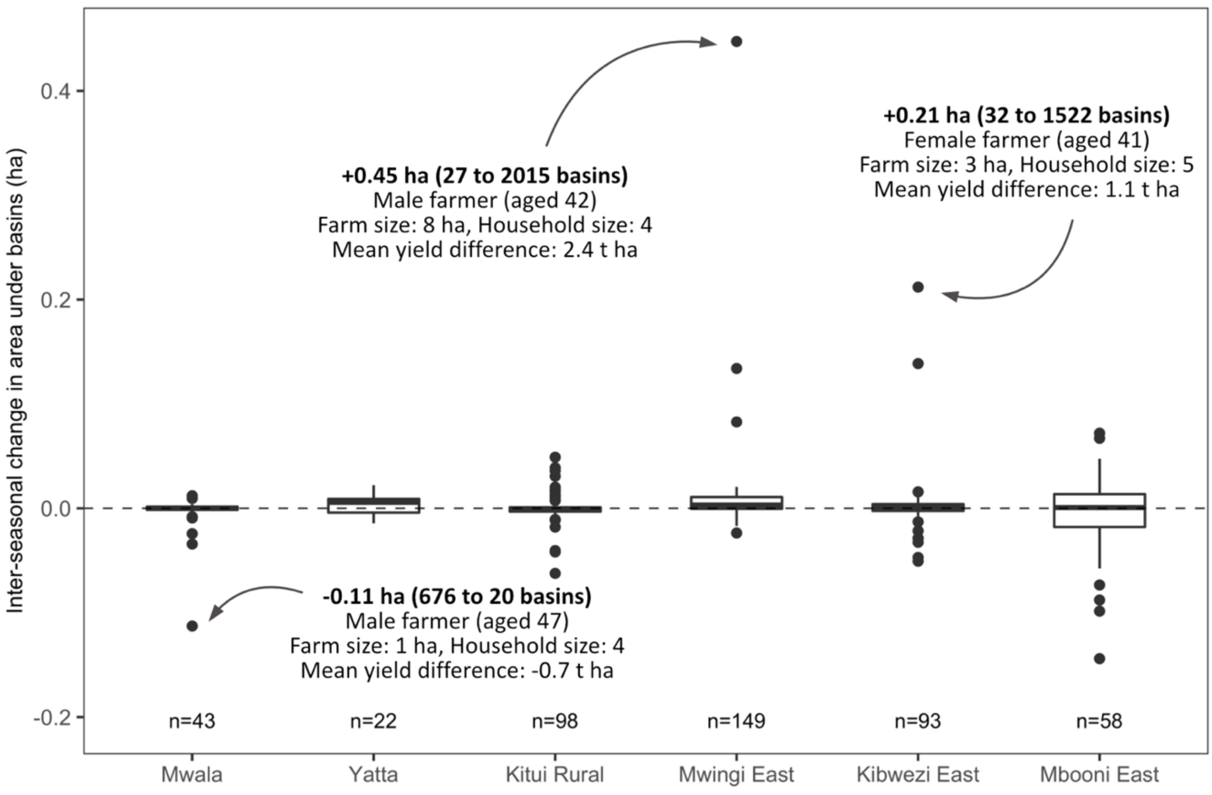

Figure 2.14 Inter-seasonal change in the area of land under basins for a subset of 376 households that were assessed in two or more seasons. Most farmers did not increase the area of their farm under basins between monitoring seasons. Farmers that substantially increased or decreased the area of their farm under basins between seasons are highlighted along with some of the details for these farmers, including the yield difference they experienced from their basin plots.

3.4 Profitability analysis

In our quest to translate yield increases into the specific livelihood benefits households received, we conducted a simple profitability analysis for each tillage system including gross margins and returns to labour per hectare. We then estimated the personal daily income for each household member.

Note: Monitoring surveys largely focused on productivity and failed to capture the input costs associated with all agronomic operations – only the estimated time farmers took to prepare their plots using a specific tillage system were collected (for basin plots this included the time taken to dig them for the first time and the time take to re-dig them in subsequent seasons). Our profitability analysis therefore makes several assumptions regarding the labour and input costs of each tillage system (see S2.5, Appendix 7 for details). Our results should thus only be taken as estimates.

3.4.1 Gross margins

The median gross margins varied widely across the four different tillage systems, ranging from -115,213 to 68,849 Ksh ha^{-1} (-2,767 to 1,654 USD ha^{-1}) for small and large basins, respectively (Table 2.16). The smallest size of basin was, on average, considerably less profitable than farmers' current tillage systems – for both hand hoe and ox plough cultivation. Although medium and large basins provided a similar median yield, they differed in profitability. Large basins were the most profitable with a median gross margin of 42,087 and 68,849 Ksh ha^{-1} for first digging and subsequent repairs, respectively. Medium basins, on average, only became profitable after their initial digging, with median gross margins of -22,537 and 42,688 Ksh ha^{-1} for digging and repairing, respectively. This is likely because of the higher labour costs associated with digging and repairing medium sized basins. During farmer workshops, farmers reported that the small basins were not only less productive compared to large basins but more difficult and time consuming to dig. This is presumably also the case for medium basins (i.e., the bigger the basin the easier to dig and the less time consuming per hectare) and is corroborated by our survey data. It was estimated to take a median of 206 person-days ha^{-1} to dig the small basins (assuming 12,346 basins ha^{-1}), 145 person-days ha^{-1} to dig the medium basins (assuming 6,944 basins ha^{-1}), and 74 person-days ha^{-1} to dig the large basins (assuming 4,444 basins ha^{-1}). After establishment, the basins were reported by farmers to only require repairing. Based on our survey data, repairing basins was estimated to take on average half of the time as their initial digging. These times are roughly in line with those reported by Schuler *et al.* (2016) for small basins (20-30cm in diameter) in Burkina Faso at 90-120 person-days per hectare for the initial digging.

Similar to yield difference, we saw large variation in within-farm differences in gross margin, with farmers' usual tillage practices outperforming basins for many farmers (Figure 2.15). 92% and 44% of small and medium basin plots, respectively, were equally or less profitable than their paired farmer practice plots, compared to only 17% of large basin plots. The median value-cost ratios for basins revealed a similar picture and ranged from -0.24 to 3.4 for small and large basins, respectively.

Table 2.16 Profitability analysis and returns to labour for all plots and seasons.

	Farmer practice		30x30cm basins		60x60cm basins		90x90cm basins	
	Hand hoe (n = 395)	Ox plough (n = 1417)	First dig (n = 123)	Repair[4] (n = 118)	First dig (n = 1117)	Repair[4] (n = 875)	First dig (n = 636)	Repair[4] (n = 505)
Grain yield ($t\ ha^{-1}$)	0.30 (0.12, 2.07)	0.81 (0.21, 1.86)	0.80 (0.21, 0.93)	0.80 (0.21, 0.85)	2.50 (1.20, 4.05)	2.77 (1.11, 4.71)	2.43 (1.82, 6.25)	3.54 (2.14, 6.36)
Income[1] ($Ksh\ ha^{-1}$)	9,074 (3,539, 62,032)	24,161 (6,388, 55,780)	24,000 (6,250, 27,857)	24,000 (6,250, 25,536)	75,000 (36,000, 121,574)	83,151 (33,333, 141,266)	72,939 (54,502, 187,460)	106,061 (64,152, 190,795)
Land preparation[2] ($Ksh\ ha^{-1}$)	2,344 (2,344, 2,344)	492 (492, 492)	115,741 (28,935, 144,676)	34,722 (17,361, 57,870)	97,656 (48,828, 130,208)	32,552 (16,276, 65,104)	31,250 (20,833, 62,500)	16,667 (10,417, 31,250)
Total costs[3] ($Ksh\ ha^{-1}$)	8,081 (8,081, 8,121)	6,230 (6,230, 6,433)	121,463 (36,482, 150,398)	40,444 (23,083, 63,592)	103,378 (54,550, 135,930)	38,274 (23,823, 70,826)	36,972 (26,555, 68,222)	22,389 (16,139, 36,972)
Gross margin ($Ksh\ ha^{-1}$)	-1,015 (-5,292, 53,951)	17,893 (85, 49,402)	-115,213 (-125,398, -25,162)	-27,368 (-38,592, -5,218)	-22,537 (-83,848, 41,505)	42,688 (-25,099, 104,354)	42,087 (4,932, 120,364)	68,849 (42,755, 154,124)
Gross margin (PPP \$ ha^{-1})	-24 (-127, 1,296)	430 (2, 1,187)	-2,767 (-3,012, -604)	-657 (-927, -125)	-541 (-2,014, 997)	1,025 (-603, 2,506)	1,011 (118, 2,891)	1,654 (1,027, 3,702)
Returns to labour[2] (Ksh person-day)	-23 (-152, 1,645)	716 (3, 1,917)	-188 (-208, -141)	-138 (-188, -33)	-57 (-173, 218)	254 (-123, 840)	333 (17, 455)	732 (365, 1,289)
Labour productivity (kg person-day)	7.24 (3.16, 63.03)	32.23 (8.56, 72.34)	1.25 (0.58, 2.88)	2.98 (1.37, 6.62)	5.64 (1.80, 14.90)	16.12 (3.45, 35.62)	18.79 (8.21, 22.88)	32.22 (19.88, 50.82)
Value-Cost ratio	---	---	-0.08 (-0.18, 0.18)	-0.24 (-0.56, 0.45)	0.50 (0.13, 1.37)	1.16 (0.22, 4.05)	2.23 (0.67, 3.01)	3.48 (0.32, 5.28)

Statistics presented: Median (IQR)

[1] Based on estimates from local community facilitators for the price of maize during times of surplus (30 Ksh per kg).

[2] Labour costs assume a day rate of 225 Ksh based on the basic wage for an unskilled labourer within the agricultural industry (KNBS, 2020). Person days per ha for farmer practice were not collected in 2018 and 2019, median values from 2017 are thus used instead (10.42 days/ha and 2.19 days/ha, for hand hoe and ox plough cultivation, respectively).

[3] Additional labour costs for planting (5.14 days/ha for basins only) and manure application (8.11 days/ha and 2.84 days/ha for farmer practice and basins, respectively) are based on Nyamangara et al. (2014). Weeding under farmer practice assumed to take a similar time to the median time for hand hoe cultivation in 2017 and that weeding basins takes half the time (based on farmer reports). Price of seed based on community facilitator estimates (70 Ksh per kg of local seed) and a plant population of 3.5 plants m^2 for all treatments. Harvesting assumed to take 11.97 days/ha based on Mazvimavi and Twomlow (2009).

[4] Fewer observations for repair years is due to farmers in 2018 and 2019 only being asked for estimated time to re-dig if they had re-dug basins that season.

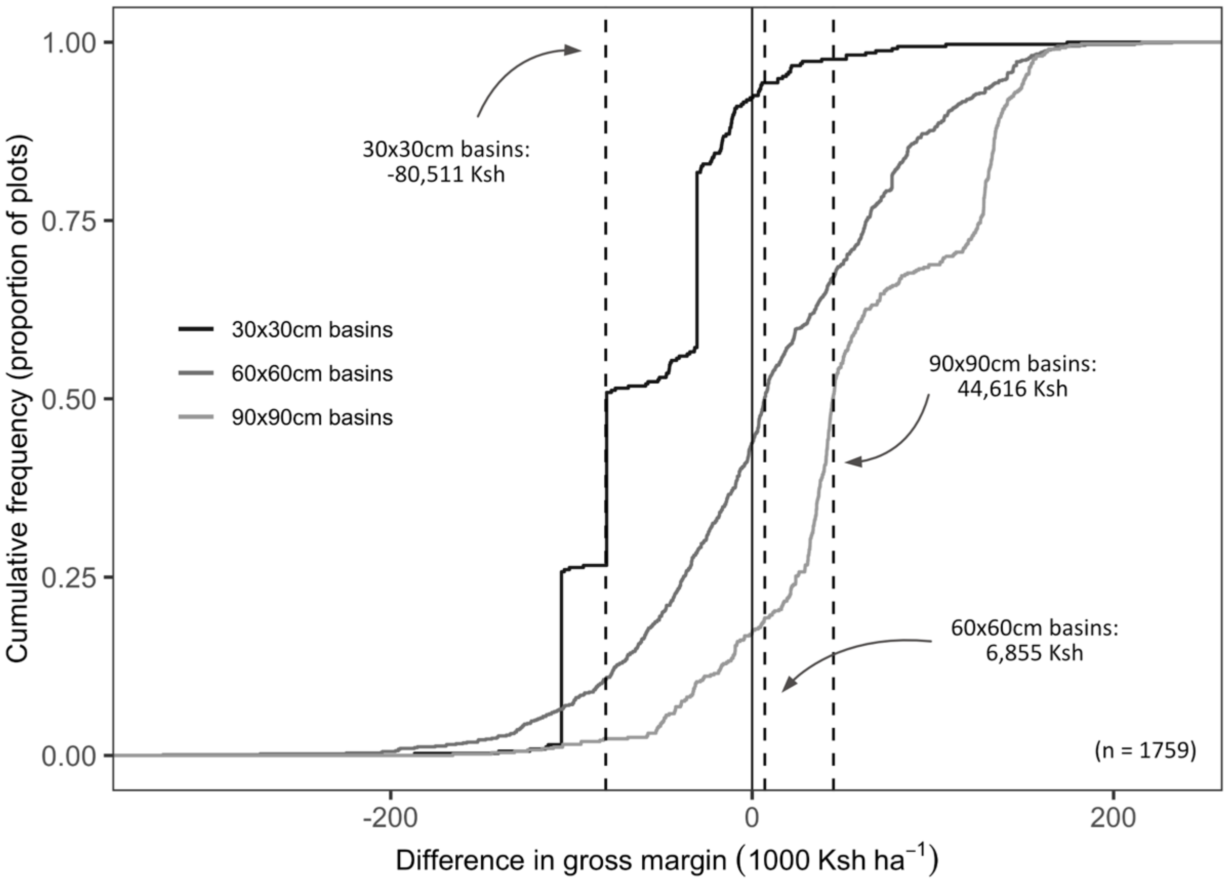

Figure 2.15 Cumulative frequency curves showing the distribution of within-farm difference in estimated gross margin (Ksh ha^{-1}) between basin and farmer practice plots (using gross margins for repairing basins, rather than their initial digging). Dashed lines show median difference for each basin size. Large basins (90x90cm) increased gross margins for most farmers while small basins (30x30cm) reduced gross margins for many farmers.

3.4.2 Returns to labour

In order for agricultural innovations to be adopted they not only need to be productive and profitable, they also need to be attractive within the wider context of smallholder livelihood systems. In the drylands of eastern Kenya, few households rely solely on farming to earn a living. Thus, agricultural innovations not only need to compete against existing and alternative farming options, but also off-farm income opportunities. To assess whether digging basins is likely to be an attractive livelihood option to family members or would justify hiring external labour, in Figure 2.16 we compared returns from each tillage system and average wage rates for different off-farm occupations, ranging from a local agricultural labourer to a skilled artisan working in Nairobi.

On average, only the large basins outperformed ox plough cultivation (the most common tillage practice among farmers) and only marginally (Table 2.16 and Figure 2.16, see Figure S2.3, Appendix 7 for cumulative distribution by monitoring season). Returns for both ox plough and large basins were comparable to that of the average wage rate for a labourer in Nairobi (i.e., 710 Ksh day^{-1}). Although we see considerably less variation in returns from medium and large basins compared to farmers' usual tillage practices, Figure 2.16 highlights the variable and uncertain returns from rain-fed maize production in our study sites. While some farmers in some seasons may have received a good return on their labour, if reliable off-farm work is available, investing labour off-farm is likely to be a more profitable and less risky option.

3.4.3 Personal daily income

While gross margins and returns to labour provide an indication of the profitability of basins at the plot level, they fail to take into consideration the impact of new technologies at the farm and household scale. In much of sub-Saharan Africa, farms are small and families are large, meaning substantial gains in yield at the plot scale do not necessarily translate into substantial production gains at the farm scale (Harris and Orr, 2014). In our final analysis, we estimated personal daily income (PDI) had each household used only basins on their cultivated land compared to if they had used their usual practice (Table 2.17). In terms of average difference in PDI, only the large basins made a sizable difference compared to farmer's usual practices, with a median increase of 0.51 to 1.27 $/person/day depending on farmer's usual practice and whether establishment or repair costs are considered. Nevertheless, based on the cumulative distribution of PDI differences (Figure 2.17), we estimate that only 29% of large basin plots would have resulted in an increase in PDI of 1.00 $/person/day or greater. These results indicate that although profitable on a per hectare basis, converting to basins is unlikely to result in large increases in per capita income for the majority of households given relatively small farms (median: 3.5 ha) and large family sizes (median: 6 persons). Furthermore, these estimates assume households have sufficient labour to convert their total cultivated area to basins. With a median cultivated area of two hectares and a labour requirement of 74 person-days per hectare for large basins, this assumption seems unlikely for most households.

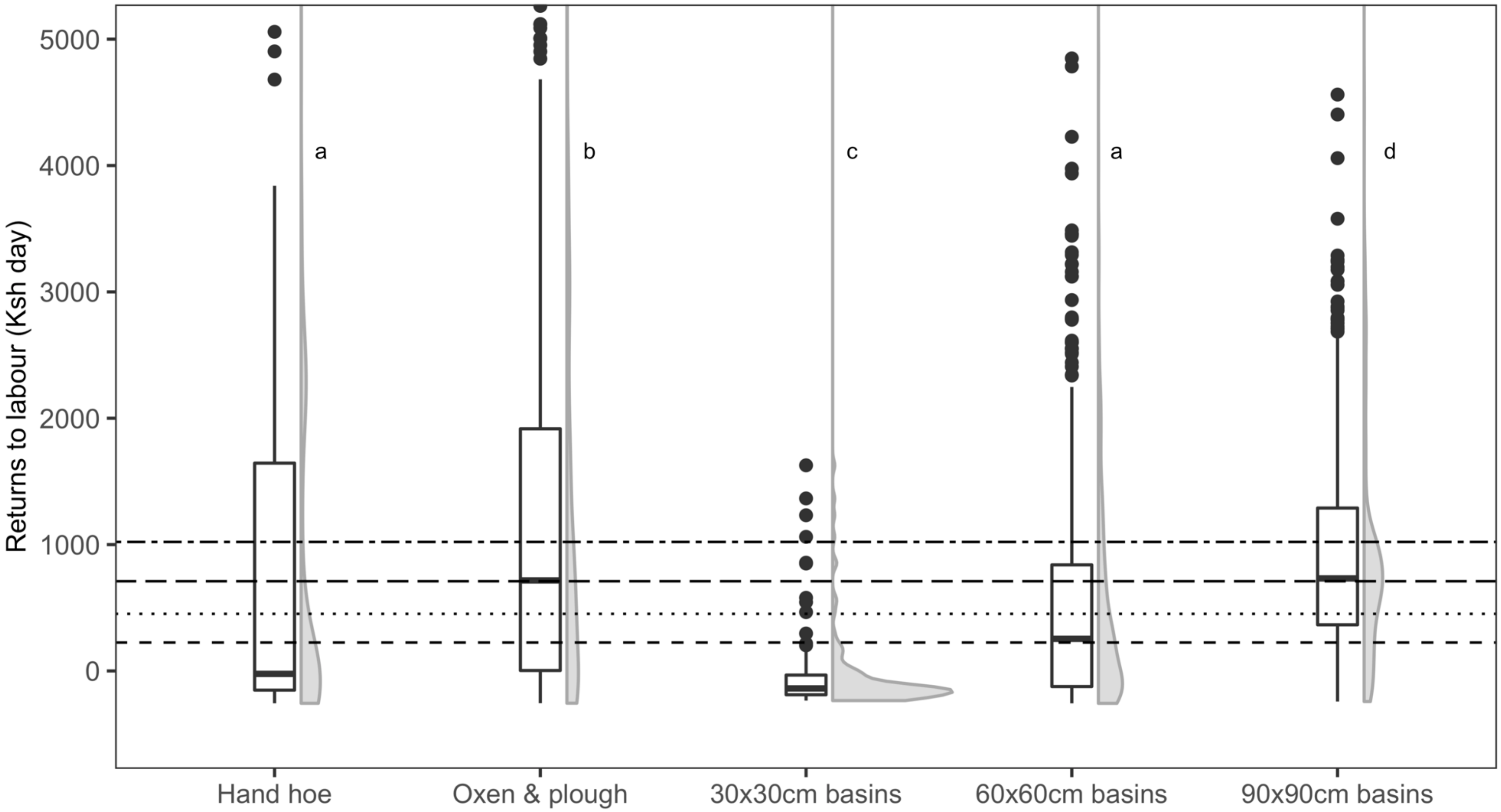

Figure 2.16 Estimated returns to labour for each size of basin and farmer's usual practice. Dashed lines show average wage rate for different occupations, from a local agricultural labourer to a skilled artisan labourer working in Nairobi. Returns to labour for basin plots based on returns for re-digging basins. Different superscript letters are significantly different ($p < 0.05$) based on pairwise Wilcoxon Rank Sum test. In terms of median returns to labour, only the large basins (90x90cm) outperformed farmers' usual practices and only marginally.

Table 2.17 Personal daily income (PDI) for each tillage system. Analysis uses a subset of 845 households for which socio-economic ata, and thus household size and area under cultivation, was collected.

	Farmer practice		30x30cm basins		60x60cm basins		90x90cm basins	
	Hand hoe (n = 324)	**Ox plough (n = 1114)**	**First dig (n = 121)**	**Repair[2] (n = 116)**	**First dig (n =924)**	**Repair[2] (n = 682)**	**First dig (n = 453)**	**Repair[2] (n = 322)**
Personal daily income (Ksh/person/day)	-1.93 (-5.62, 8.07)	10.29 (-1.26, 31.22)	-31.04 (-106.99, -22.73)	-8.81 (-33.31, -4.99)	-24.43 (-77.60, 22.74)	9.47 (-25.39, 69.85)	31.80 (-7.18, 86.87)	50.60 (14.87, 140.37)
Within-farm difference	---	---	-24.07 (-27.66, -16.87)	-18.38 (-24.09, -6.97)	-21.70 (-54.61, 3.24)	1.04 (-26.65, 46.48)	13.22 (-11.36, 42.10)	33.71 (1.52, 100.77)
Personal daily income (PPP/person/day)[1]	-0.05 (-0.14, 0.19)	0.25 (-0.03, 0.75)	-0.75 (-2.57, -0.55)	-0.21 (-0.80, -0.12)	-0.59 (-1.86, 0.55)	0.23 (-0.61, 1.68)	0.76 (-0.17, 2.09)	1.22 (0.36, 3.37)
Within-farm difference	---	---	-0.58 (-0.66, -0.41)	-0.44 (-0.58, -0.17)	-0.52 (-1.31, 0.08)	0.03 (-0.64, 1.12)	0.32 (-0.27, 1.01)	0.81 (0.04, 2.42)

Statistics presented: Median (IQR)
[1] PPP based on ICP benchmark PPP 2017 for household's final consumption expenditure (41.64 Ksh per international dollar).
[2] Fewer observations for repair years is due to farmers in 2018 and 2019 only being asked for estimated time to re-dig if they had re-dug basins that season.

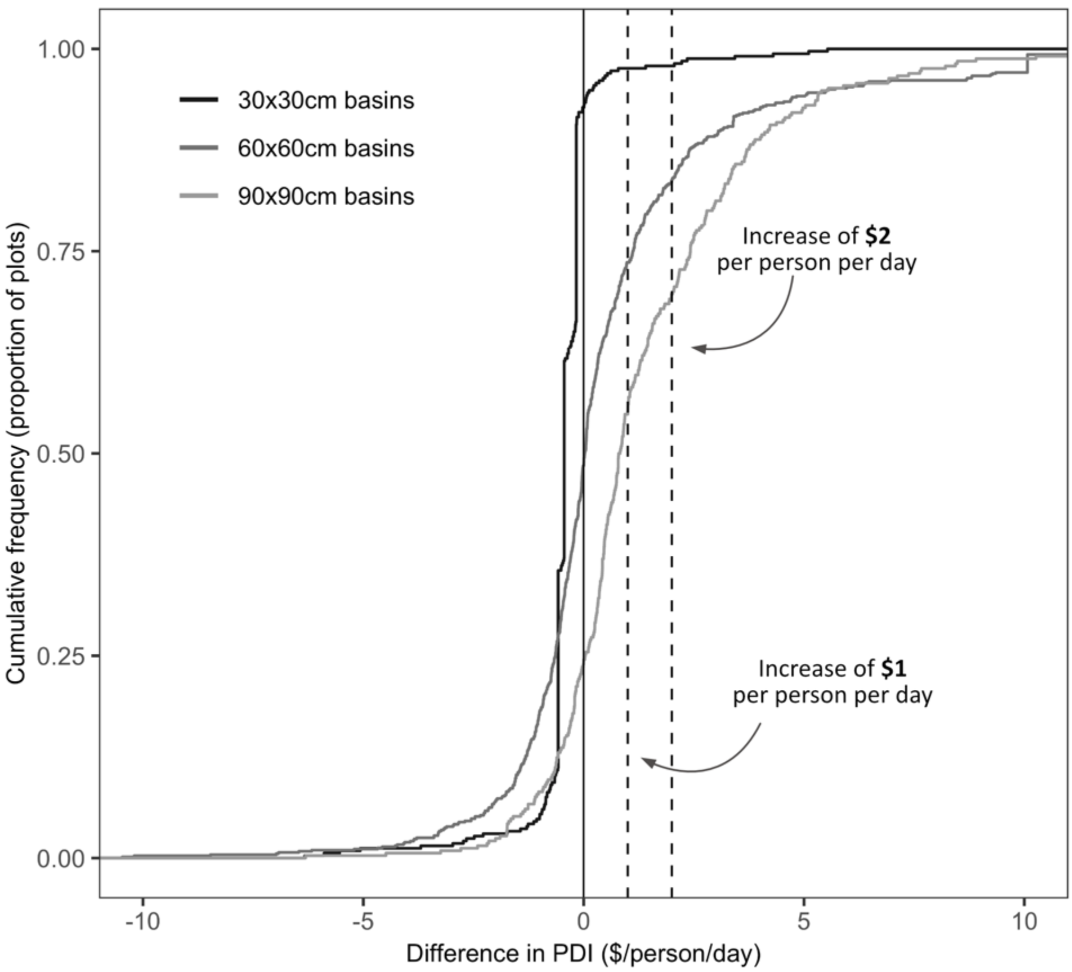

Figure 2.17 Cumulative frequency curves showing the distribution of within-farm difference in personal daily income for different sizes of basin. Vertical lines (dashed) indicate differences of 1$ per person per day and 2$ per person per day. Analysis uses a subset of 845 households for which data on household size and cultivated area were collected. Large basins (90x90cm) increased personal daily income for most farmers while small basins (30x30cm) reduced personal daily income for most farmers.

4. Discussion

4.1 The efficacy of basins

Based on our analyses we can offer several new insights and recommendations for using planting basins in the eastern drylands of Kenya. First, that small basin – 30x30cm in diameter and closer in design to those commonly promoted in West Africa (i.e., Zai pits) – perform poorly in comparison to larger sizes of basin (i.e., 60x60cm and 90x90cm). Second, that contrary to current recommendations suggesting basins are best suited to areas receiving 300-800 mm of rain per annum (Mupangwa et al., 2008; Nyanga et al., 2012; Schuler et al., 2016), we found planting basins can perform well even under higher rainfall conditions, although this could well be attributed to the fact that farmers modify the structures in response to heavy rainfall. Based on our interactions with farmers, these insights likely reflect that smaller basins are prone to backfilling with sediment following heavy rains and quickly lose their ability to capture surface water run-off. This observation is supported by Amede et al. (2011) in Ethiopia. Lastly, consistent with current advice using basins in combination with farmyard manure improves their efficacy, especially when larger basins are used.

While our results provide further evidence that basins can, in some cases, provide impressive gains in terms of average maize yields (Table 2.1), they also highlight the potential for wide variability in treatment effect between farms. For some households, basins provided substantial yield increases, extra days of food for their family and a potential income boost, while for others the use of basins translated into substantial losses. This variation in treatment effect poses considerable risk to farmers when planting basins are promoted and adopted as a generalised recommendation – even if larger basins combined with farmyard manure were to be promoted.

We found sub-county to explain large amounts of variation in yield effect. Yet, knowing that basins work well in some sites and not others (although potentially useful for programmatic decisions) provides little insight into what might happen in other locations – what is it about the difference between sub-counties that governs the performance of basins? However, what it does suggest, is that missing explanatory factors are likely to vary at the sub-county level. For example, one factor we did not capture in our analyses that is known to influence the performance of basins is soil texture. Given its influence on surface water run-off and infiltration rates, soil texture is often used as a selection criterion for selecting suitable sites for planting basins (Mupangwa et al., 2008; Nganga et al., 2019; Nyagumbo et al., 2016). Planting basins are reported to be inappropriate for use on soils prone to waterlogging such as vertisols and best suited to well-draining, medium textured soils, such as sandy loams, free from large stones (Danjuma and Mohammed, 2015; Mupangwa et al., 2008; Nyagumbo et al., 2016). Another potential factor overlooked by our study is slope, with basins said to be best suited to gradients of 1-15% (Malesu et al., 2007; Nganga et al., 2019). Both these factors vary at the sub-county level.A recent study that mapped areas suitable for various soil and water conservation practices in eastern Kenya, identified Kitui County as being highly suitable for the use of planting basins given the predominance of medium textured soils, low annual rainfall, and absence of steeply sloping land (Nganga et al., 2019). Encouragingly, in our study, Kitui is also the county for which we saw the highest numbers of farmers engaged in the basin planned comparison (Mwingi East and Kitui Rural sub-counties) and for which we saw the highest yield responses to basins. We therefore suggest that future studies of the potential sources of variation in basin performance consider the role of soil texture and slope in addition to other relevant biophysical factors, including soil organic carbon and erosion prevalence[10] (Vågen and Winowiecki, 2019).

Other important yet missing agronomic factors for predicting yield response that would likely improve our analyses include plant population, previous crop rotation and land use history, planting date, and the quantity and quality of manure applied (Mugi-Ngenga et al., 2021; Nyagumbo et al., 2016). Planting date, especially, is likely to have a large effect on crop yield. In Zimbabwe, Shibata et al. (2020) found that women tended to have higher yield gains from basins compared to men. They attributed this to the fact that female-headed households often plant late when using their usual practice because of limited access to draught power, and that using basins allows for early planting and thus higher yields. There are numerous interaction effects between explanatory factors that we have not yet fully explored in our data, for example, between rainfall, basin size and manure application. However, given the noisiness of our data, pulling out these effects is challenging. Another potential bias in our data could be the idiosyncratic ways in which enumerators in each sub-county collected data. Future analysis should therefore explore this potential bias, for example, including enumerator as an explanatory variable.

It is also surprising that none of the socio-economic variables included in our analysis were shown to have a strong association with yield difference, especially given the stark contrast in household characteristics such as wealth, income sources, and proximity to urban centres, between sub-counties. A potential missing explanatory factor could be farmers' relative enthusiasm for programmes and technologies aimed at improving food security. Households in our Kitui sites particularly in Mwingi East, have a high dependency on food aid and levels of

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[10] Soil erosion was only included in our models as a binary variable (i.e., whether the farmer perceived erosion to be a problem on their farm). Yet, farms are likely to exhibit strong soil erosion and soil quality gradients. Including quantitative assessment of soil erosion at the plot level could improve our model.

food insecurity (see Figure S2.4, Appendix 7). Kitui has also in the past received considerably less attention from agricultural development programmes compared to Machakos County and to a lesser extent Makueni County. It is also worth noting that planting basins have been widely promoted in Machakos County in the past, but with low uptake. Farmers in our Kitui sites may therefore place greater value on their participation in the project and the potential gains from trying a new technology. Farmers in this site might therefore spend extra time and effort in caring for their basins, thus leading to larger treatment effects.

4.2 A livelihood perspective on the role of basins

For restorative farming practices to be adopted they not only need to be productive, they also need to be attractive within the broader context of smallholder livelihood systems. As we have demonstrated, translating plot scale metrics into farm scale metrics, using even relatively simple back-of-the-envelope calculations, can provide a useful first step towards more farmer-relevant assessments. Similar to Ngoma (2018) our analyses showed that despite basins having a positive effect on maize yield for many farmers, these gains did not necessarily translate into substantial gains in household maize self-sufficiency and income, at least not at the current levels of uptake among project participants.

For all three monitoring seasons, the estimated number of medium basins needed for households to have received an additional 30 days of maize was far greater than the average number of basins farmers currently had on their farms. The low intensity of adoption by farmers (i.e., number of basins per farm) could reflect: i) that household's lack sufficient labour to dig and maintain large numbers of basins; ii) that farmers are still gaining confidence in this new practice; or iii) that farmers view basins as an insurance or diversification strategy in case of poor rains (but too labour intensive to convert large areas of their farm, especially if rains in a given season are adequate).

This latter safety-net hypothesis is corroborated by farmers' comments that while their usual farming practices may fail completely when rains are poor, they are able to harvest "*at least something, rather than nothing*" from their basin plots. Such comments indicate farmers may place greater value on the role basins play in avoiding crop failure than they do on increasing yields under higher rainfall conditions. This function is further illustrated by the fact that only

11% of plots with basins experience crop failure in OND 2017 (the monitoring season receiving the lowest rainfall) compared to 30% of plots without. Although our analysis indicates that basins provided higher yield increments with increasing in-season rainfall, yields from farmer's usual tillage systems were also high. Thus, investing in basins in years where farmers' usual tillage practices are likely to do well, may not offer the same safety-net function which farmers appear to value.

These findings suggest that basins are playing an additional role in relation to livelihoods other than maximising yield and are instead primarily being used to buffer households against climatic shocks and yield failures – a contribution that traditional performance metrics such as yield and income per hectare and intensity of adoption tend to overlook. Equating low intensity of adoption (total area or % of farm area under a new practice) with farmers not valuing an innovation misses the additional roles they may play within the livelihood system, other than maximising yield. For example, Shibata et al. (2020) deem households as adopters of conservation agriculture only if over 50% of their cultivated area is under minimum tillage (e.g. planting basins). Such classification overlooks that even small areas of basins may be playing an important function within the livelihood system. Further still, our findings reiterate the importance of including farmers' perceptions and evaluations in the assessment of agricultural innovations (see also Chapter 5).

Although our analyses attempted to translate yield increases into the specific benefits a household can expect to receive, the indirect impacts and benefits of basins (e.g., maize stover production for use as livestock) and extent to which their adoption can influence wider livelihood outcomes (e.g., livelihood resilience to increasing rainfall variability) remains overlooked given the static nature of our economic analyses. Given the limitations and cost of conducting further on-farm trials, such aspects could instead be explored through systems simulation modelling. As a next step towards a more systemic evaluation of basins, we therefore propose the development of a farm-scale dynamic system model to extend our findings beyond three seasons and to explore potential interactions between basins and other livelihood components (i.e., crop-livestock interactions) (see Chapter 3).

4.3 Importance of valuing people's labour

Our profitability analyses suggest that using planting basins, especially large basins that have already been dug, has the potential to boost returns from maize production. However, our calculation for personal daily income assumes households are able and willing to convert the whole of their cultivated land area to basins. Given that many smallholder farm households face labour constraints, this is an unlikely assumption and highlights the need to consider labour availability within households when assessing labour-intensive restorative practices.

The initial labour cost of digging large numbers of basins is likely to be prohibitive for many households. Even when the returns from basins justify the hiring of external labour, lack of cash upfront to pay labourers and lack of labourers to hire may be challenging for many households. Given that labour constraints are one, if not the primary barrier to using basins (Schuler, 2016, see also Chapter 4) finding ways to mechanise their excavation would seem to be a logical next step to help facilitate the wider uptake of the practice. Further still, one of the main production constraint basins help to alleviate is intra-seasonal dry spells during crop development. Yet, as illustrated in this study by farmers using supplementary irrigation in combination with their basins, basins alone may not be the most efficient or effective method of addressing this constraint. Other technologies such as water tanks, farm ponds, drip irrigation systems are likely to offer a less labour-intensive option to relieving crop water-stress, albeit, capital-intensive (e.g., purchasing water tanks, irrigation systems, pumps, pond liners and hiring labour to dig ponds).

The high labour demands associated with digging basins also raise the question of whose labour will be used and how this labour is valued. Several studies have reported a shift in labour burden from men to women with the uptake of basins, with women becoming more involved in land preparation – an activity traditionally carried out by men (Baudron et al., 2007; Nyanga et al., 2012). Given that women are often primarily responsible for much of the work within the home, increases in their farm work risks increasing their already heavy workloads (Njuki et al., 2016). A critical area for further investigation is thus understanding how planting basins influence the workloads of men and women following their uptake and the potential changes in gendered divisions of labour (see Chapter 4).

4.4 Recommendations for conducting research in development

Several lessons emerge from our study in relation to potential tensions between large-scale farmer engagement and conducting controlled field experiments. One advantage of using planned comparisons is farmer learning. Rather than being prescriptive, the approach encourages adaptation to local circumstances (Coe et al., 2017). Farmers had ownership of the comparisons and could decide which options they compared each season, allowing them to implement what they learnt throughout the trial. For example, many farmers decided not to test the small basins once they were shown to be less productive than larger basins. Some had chosen to use a different spacing between their basins than that prescribed during training workshops. Others were seen complementing their basins with supplementary irrigation. This farmer-centred approach to on-farm trials is likely one of the reasons for the impressive number of farmers participating in the project.

Variation in implementation and management of innovations can present challenges when it comes to data collection and analysis, especially when data on such aspects have not been collected. Ideally, as researchers, we would have wanted farmers to continue with the same comparisons for multiple seasons so as to capture variation in performance under different climatic conditions. For instance, since only a few farmers tested the small basins in OND 2018 and OND 2019, we were unable to ascertain how small basins perform under higher rainfall conditions. Similarly, we saw differential treatment between matched basin and farmer practice plots. Many farmers had decided to locate their basins close to the household and to use improved maize varieties and manure in their basin plots and not their control plots. Given the additional benefits of using drought-tolerant varieties, farmyard manure and the potential for extreme soil fertility gradients even within the same farm (Tittonell et al., 2013), differences in management make it challenging to determine whether within-farm yield differences are driven by the basin structures themselves or by these other management factors. At least some of the unexplained variation in our analyses could well be because of this differential treatment between basin and non-basin plots (Laajaj et al., 2020; Sileshi and Akinnifesi, 2019).

Widespread adaptation in the size and spacing of basins is also reported by Bunderson et al. (2017) among farmers in Malawi, yet the authors attribute this variation to poor understanding and delivery of the technology rather than farmer experimentation. Regardless of whether farmers are actively encouraged to adapt innovations, farmer adaptation and variation in implementation is likely to occur when conducting on-farm trials and promoting new technologies and needs to be adequately captured.

A recent public debate between Coe, Njoloma and Sinclair (2019) and Sileshi and Akinnifesi (2019) offers several reflections on the desired level of experimental control in on-farm trials. Sileshi and Akinnifesi (2019) criticise Coe and colleagues (Coe et al., 2016) for failing to consider discrepancies in management between treatment and control plots in their analysis of yield differences (in this case, from on-farm agroforestry trials conducted in Malawi). In their rebuttal, Coe and colleagues argue that changes in the way farmers manage plots in response to an innovation reflect real-life behavioural responses and how farmers integrate innovations into their farming systems. Differences in management between treatment and control plots should thus be considered part of the system response to an innovation and not be discounted. Indeed, the need to incorporate variation in the way farmers implement and manage innovations is one of the core tenets for the increased use of farmer-managed on-farm trials over the past decades (Laajaj et al., 2020).

Nevertheless, Coe and colleagues' argument rests on the assumption that the differential management between treatment and control plots does in fact reflect farmers' real-life behavioural responses to an innovation. In our study, farmers' preferential treatment of basin plots might reflect farmers behavioural response to planting basins and the role they play in reducing risk of crop failure (thus, farmers are more willing to make additional investments such as using costly seeds and adding manure). Alternatively, it could also reflect biases induced by the artificiality of experimental circumstances and high levels of researcher engagement in the project. As Lajaaj *et al.* (2020) point out, farmers may pay more attention, care and effort in trials than in their usual farming. The very fact of knowing that plots are part of an experiment (and that enumerators and researchers overseeing trials may even praise and showcase those whose treatment plots perform well) is likely to influence farmers' behaviour and thus deviate from real life conditions. The high levels of researcher-farmer engagement and knowledge sharing, although likely behind the high numbers of farmers trying out the basins (Nyanga et al., 2012), may well have contributed to such biases. Farmers were not only visited by enumerators most growing seasons but were offered training in how to dig basins twice a year, visited by project donors and journalists, and invited to attend annual workshops to share their insights and provide feedback on project activities.

We also recognise that there are likely many other sources of biases in our study, including farmer selection, i.e., farmers participating in the trial were self-selected and thus are unlikely to be representative of the wider farming population in our study area. It should also be noted that, while no financial incentives or additional support was given to farmers other than training, most of the farmers involved in the planting basin planned comparison were also involved in the tree planting planned comparison where farmers were provided with tree seedlings at no cost.

The conundrum of what and how much to control also raises important questions around research ethics. For example, while we, as researchers, would ideally like to have replicates of treatments over multiple seasons, it is arguably unjust to expect farmers, who are often resource poor and food insecure, to continue investing their valuable time and resources in options that they know do not work well, particularly without any form of compensation. In summary, there are inevitably trade-offs involved with all types of trials but there are also clear complementarities. On the one hand, researcher-managed trials, offering more control over external factors, are well suited to understanding and isolating the biophysical impacts of treatments (Coe et al., 2019). On the other hand, more collegial and farmer-managed trials better reflect smallholder farming conditions and are well placed for exploring variability in treatment effect as experienced by farmers (Coe et al., 2019; Franzel and Coe, 2002). Both are needed if we are to provide farmers with relevant and effective recommendations for their circumstances. Yet, as we have shown, understanding the causes of variation in performance across farms requires that data on relevant explanatory factors are collected but that this can be challenging, especially when engaging large numbers of farmers and encouraging farmer adaptation. Based on the findings and reflections presented in this study, we offer the following recommendations for future projects embracing the RinD approach and implementing planned comparisons:

i) Complement on-farm planned comparisons with an initial phase of more controlled, small-scale trials with a select number or farmers before scaling up to large numbers. This can help ensure potential farmer adaptations are captured early and inform what factors will be important to capture in further monitoring. This initial phase of data collection should include qualitative local knowledge studies to see how and why farmers are choosing to adapt innovations (Dumont et al., 2019).

ii) Keep trial designs simple and encourage farmers to compare only a limited set of options, emphasising the importance of comparing like for like (i.e., encourage farmers to maintain comparable plots managed in the same way);

iii) Co-develop monitoring surveys and protocols with farmers to help to ensure farmer-relevant performance metrics are captured and to guide data analysis, and;

iv) Conduct timely analyses of monitoring data to allow surveys in subsequent seasons to be improved upon and ensure key agronomic management factors and farmer adaptations are reliably and adequately captured.

5. Conclusion

Providing smallholder farmers with relevant recommendations requires a systemic approach to assessing the performance of restorative farming practices and a realistic understanding of their transformative potential in resource constrained environments. In this study, we attempted to build upon the work of Coe and colleagues, not only by examining variability in innovation performance between farms, but by taking our analyses one step further and translating within-farm yield differences into the farm-scale metrics that matter to households and their members. We show that even relatively simple back-of-the-envelope calculations can be a useful first step towards more farmer-relevant assessments. Based on our analyses we make several general recommendations on the use of planting basins in the eastern drylands of Kenya. However, although we found that planting basins had an impressive mean effect on maize yield compared to farmers' usual tillage practices, we also revealed large variation in response across farms and between sub-counties. This variation poses considerable risk to farmers when basins are promoted as a generalised recommendation. While understanding the causes of variation in yield response can help identify the conditions under which innovations are most likely to have a positive effect, this requires the collection of data on relevant factors. As we demonstrate, this can be challenging especially when engaging large numbers of farmers and encouraging on-farm adaptation of innovations. Whether or not farmers are actively encouraged to adapt innovations, farmer adaptations are likely to occur when conducting participatory on-farm trials. Researchers therefore need to accept that farmers modify practices and adequately document farmer adaptations and capture interactions between adoption and adaptation. Based on our findings and experiences, we offer several recommendations for future projects implementing a planned comparison approach.

Chapter 3: Developing and applying a farm-scale model for assessing the impacts of planting basins on smallholder livelihood systems

An adapted version of this chapter is in preparation for submission to Agricultural Systems. Initial results were also presented at the CGIAR Research Program on Policies, Institutions and Markets (PIM) Workshop on Rural Transformation in the 21st Century at the International Conference of Agricultural Economists (ICAE), Vancouver, Canada, July 2018.

1. Introduction

Maize (*Zea mays L.)* is the main staple food crop grown in Kenya. Produced predominately by smallholder farmers and providing over a third of people's daily caloric intake, variation in its production has severe consequences for people's livelihoods and basic food security (Mohajan, 2014; Nyoro et al., 2007). Despite a steady increase in average maize yield from 1.2 t ha^{-1} in 1980 to 1.8 t ha^{-1} in 2019 (FAOSTAT, 2021), current maize yields in Kenya remain well below potential yields, with an estimated yield potential under rain-fed conditions of 7.9 t ha^{-1} (GYGWPA, 2021). Pervasive challenges to closing this yield gap include increasingly erratic rainfall, widespread soil erosion and declining soil fertility (Muoni et al., 2020; Okoba and Sterk, 2010). With Kenya's population projected to more than double between 2010 and 2050 (UN, 2015), meeting future food demand will require a rapid increase in crop production, including that of maize, and widespread uptake of farming practices that increase agricultural productivity and resilience to climate variability while reducing and reversing soil degradation processes.

One such practice increasingly promoted in the drylands of Kenya is the use of planting basins, a soil and water conservation technique where small pits are dug, usually in a grid formation, and crops planted within them (Kimaru-Muchai et al., 2020; Muriu-Ng'ang'a et al., 2017; Ndeke et al., 2021). These basins, typically used in combination with nutrient-rich compost or manure, reduce surface water run-off and increase soil water availability, helping to bridge intra-seasonal dry-spells and improve plant survival and growth. Across sub-Saharan Africa (SSA), substantial yield increases have been reported in arid and semi-arid areas when planting basins are used, including for the production of maize (Muli et al., 2017; Oduor et al., 2021; Rockström et al., 2009; Schuler, 2016). Yet, despite these impressive yield effects, few studies have assessed the extent to which basins can contribute to transformational change in household food security and livelihood outcomes.

Evaluations of the performance of planting basins have largely focused on plot scale metrics, such as average yield or income per hectare, or partial budget analyses using data collected from short-term trials (e.g., limited to a few seasons), and generally assume that positive yield increases will translate into positive outcomes at the household level (see Table 2.1, Chapter 2). However, in much of SSA, farms are small and families are large, meaning substantial yield gains at the field scale do not always translate into substantial gains in food availability and income at household scale (Harris and Orr, 2014; Verkaart et al., 2018). Furthermore, narrow evaluations, while adequate for tracking the immediate effects of simple technological innovations, often underplay more complex innovation in natural resource management that may catalyse a cascade of interactions amongst livelihood components (Sinclair, 2017; van Ginkel et al., 2013). Even when agricultural innovations are unlikely to lift the majority of smallholder farmers out of poverty on their own, they may have indirect and far-reaching implications on the wider livelihood system and households' capacity for transformational change.

In addition to boosting yield, using planting basins could result in additional livelihood benefits for many households. For instance, through redistributing farm labour demand throughout the year and freeing up labour for alternative and potentially more lucrative income-generating activities, or through providing greater yield stability under variable rainfall conditions and a critical safety-net in terms of household food security. Relying solely on economic cost-benefit analyses and plot-scale performance metrics overlooks the more complex interactions between innovations and livelihood components and activities. Taking a more systemic perspective to the evaluation of innovations is thus likely to give a better idea of which agricultural options are attractive to smallholder farm households and under what conditions, helping to match options to different farm and farmer circumstances (Coe et al., 2014; Descheemaeker et al., 2019).

A common feature of farming systems research is the development and application of farm-scale simulation models (Descheemaeker et al., 2019; Thornton and Herrero, 2001; van Wijk et al., 2014). Through representing key system processes and interactions between multiple livelihood components, such models offer a valuable tool for exploring the ex-ante impacts, trade-offs and viability of promising agricultural innovations, and deepening our understanding of how farm systems might respond to proposed system changes. Farm simulation models are particularly powerful for exploring variability of production and system performance. Unlike static models and cost-benefit economic analyses, they allow for temporal variability and track the changes in states and rates over time and are capable of capturing non-linear system behaviour (e.g., reinforcing and balancing feedback loops). In doing so, they allow us to scale-up, in space and time, the effect of interventions applied at the plot level, and to evaluate their potential consequences at the farm and household scale and over longer-term time frames (e.g., Stephens et al., 2012; Tittonell et al., 2010; van Wijk et al., 2009). Through comparing the performance of different intervention scenarios before undertaking them, modelling can provide a cost-effective and low-risk tool for screening agricultural options based on current knowledge, so that farmers can be offered suites of 'best fit' technologies to choose from (Descheemaeker et al., 2019; Vanclay et al., 2006).

In this study, we describe the initial development and application of a farm-scale household model for assessing the extent to which planting basins can contribute to transformational change in household food security and livelihood outcomes in the eastern drylands of Kenya. We use a novel modelling approach involving the dynamic integration of two modelling environments: i) The Agricultural Production Systems Simulator (APSIM), an internationally recognised platform for modelling agricultural systems that incorporates a wide variety of validated crop models and a detailed soil-water component (Holzworth et al., 2018); and ii) Simile, a highly flexible tool for modelling socio-economic dynamics and management strategies at both the household and community level (Muetzelfeldt and Massheder, 2003). The intention behind combining these two modelling tools is the ability to construct models that can provide credible estimates of the effect of a wide variety of agricultural innovations under a range of farming circumstances and agroecological settings. This study provides one of the first use cases for integrated APSIM-Simile models.

The aims of developing this model were three-fold: i) to move beyond plot level assessments of planting basins and to evaluate their performance at the farm and household level; ii) to extend the results from participatory on-farm trials of planting basins conducted in Kenya across multiple years, including an exploration of basin performance under varying rainfall conditions; and iii) to explore the utility of APSIM-Simile integrated models in providing households with context-sensitive recommendations and screening promising agricultural innovations.

2. Methods

2.1 Focus region

Our model was developed as part of a land restoration project in the drylands of eastern Kenya (World Agroforestry, 2020). This semi-arid region is characterised by small-scale, rain-fed mixed farming and subject to frequent drought and crop failures caused by increasingly unreliable rainfall (KNBS, 2019). Agricultural productivity is further limited by extensive land degradation and many rural households experience food insecurity (KFSSG, 2019). To combat these challenges, planting basins have been increasingly promoted in the area, yet questions remain regarding the tangible benefits to smallholder farm households and the performance of basins under different agro-ecological contexts. Over a five-year period (2015-2020), the project worked with around 1,500 smallholder farmers across six sub-counties in Machakos, Makueni and Kitui County to conduct on-farm planned comparisons of planting basins against their usual farming practices, so as to better understand which options work best where and for whom. Data on the performance and use of planting basins collected from these on-farm trials in 2017, 2018 and 2019 (see Chapter 2) were used to inform the design and development of our model.

2.2 Modelling approach

In order to build a complete farm-scale model, we dynamically linked an APSIM biophysical model with a Simile management model. We chose to integrate these two modelling platforms for several reasons. First, Simile[11] is a highly flexible systems modelling tool that offers a platform for modular modelling, where sub-models created for one model can be easily adapted and integrated into another (Muetzelfeldt and Massheder, 2003). This function allows models to be customised for different household situations and farming contexts. Secondly, Simile is an icon-based modelling environment with an intuitive user interface and does not require extensive programming knowledge (see Figure S3.1, Appendix 7, for an example of the Simile user interface). This allows for rapid model construction and facilitates a collaborative approach to model development since the structure and function of models can be easily communicated. Lastly, unlike other dynamic systems modelling programs (e.g., STELLA, Vensim), Simile is capable of simulating both continuous and discrete events and their interaction. This has an advantage for modelling farming systems since certain processes, such as the transfer of biomass within the system (e.g., purchasing and selling crops) may occur instantaneously rather than as a continuous flow. For biophysical modelling, we chose to use APSIM[12] Next Generation, an agricultural modelling system which offers a detailed soil-water component and well-established maize crop model which has been calibrated for a wide range of climates and

[11] www.simulistics.com
[12] www.apsim.info

cultivars, including those used by smallholder farmers in the drylands of Kenya (Holzworth et al., 2018).

Combining Simile with APSIM allows for models capable of both realistic crop yield predictions and capturing a wide range of farm management and livelihood investment strategies. This is made possible through the recently developed APSIM-Simile interface (Simulistics, 2020). This interface allows users to link Simile and APSIM models, whereby the two models run concurrently with each other, exchanging information at each time step, including management statements (when to sow, when to harvest, etc.) and inputs/outputs (manure applied, crop yield, etc.). For example, in the case of our farm-scale model, farm management actions, such as sowing, fertilizing and harvesting, are communicated from Simile to APSIM, while biophysical outputs from APSIM, such as maize yield and soil state variables, are fed back into Simile (Figure 3.1).

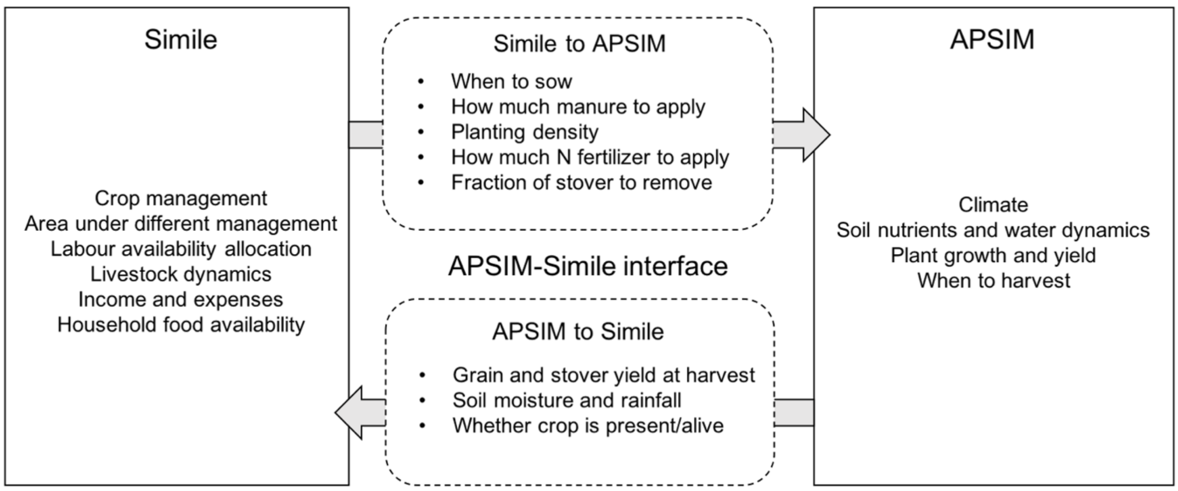


Figure 3.1 Representation of the various aspects of our model handled by APSIM and Simile, and communicated through the APSIM-Simile interface.

2.3 Model description

Our farm-scale model describes a simplified version of a smallholder farm household in eastern Kenya. These households typically pursue a mixed livelihood strategy, growing food crops primarily for subsistence, rearing small livestock herds, engaging in skilled or unskilled off-farm work and receiving cash transfers in the form of remittances from family members elsewhere (Ifejika Speranza et al., 2008). The model therefore has three main submodels that interact with each other over the course of the simulation run: a household model, a livestock model, and a crop model (Figure 3.2). Description of key model parameters can be found in Table S3.1, Appendix 7.

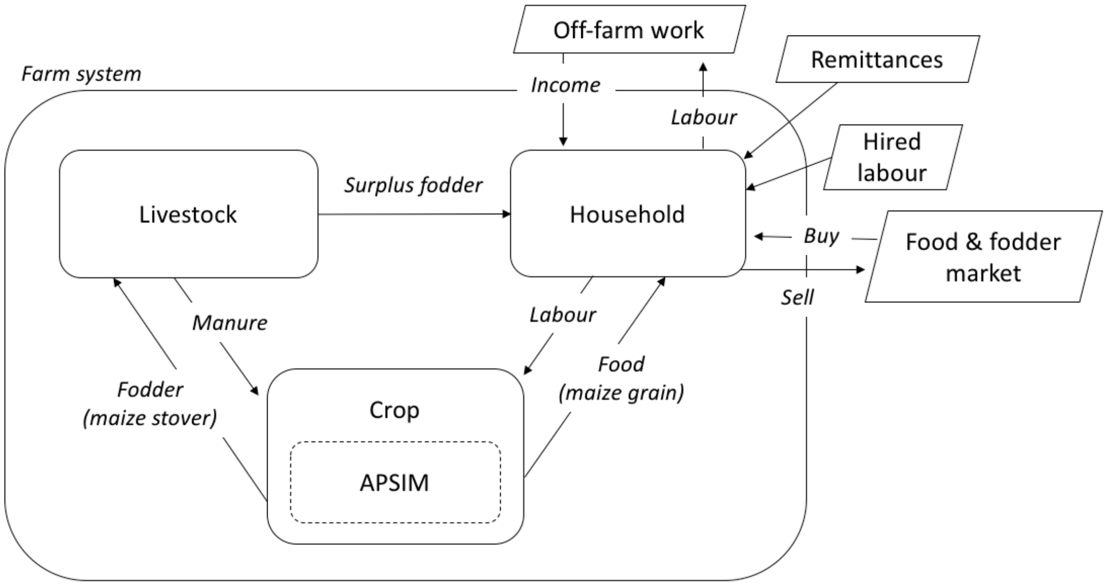


Figure 3.2 Conceptual representation of the farm-scale model and its main submodels. Arrows indicate the main flows and influences between submodel and other components.

Given our focus on the use of planting basins for growing maize, the only crop considered within the model is maize and the only livestock fodder explicitly considered is maize stover (an important feed resource on smallholder farms during the dry season). Similarly, the only livestock considered are cattle given their crucial role in nutrient cycling and income generation. In terms of the household budget, the only income and expenditures considered are the purchase and sale of maize grain and stover, off-farm income, cash remittances and the cost of any hired labour. Unlike other farm household models, which typically use a monthly or seasonal timestep (e.g., Stephens et al., 2012; Tittonell et al., 2010; van Wijk et al., 2009), our model runs on a daily time-step, allowing for consideration of daily changes in labour allocation, variation in planting date and the impact of intra-seasonal dry spells on final crop yield.

2.3.1 Household submodel

The household submodel describes the household in terms of its members, their maize requirement and ability to provide labour. It also contains the household's store of grain, stover and cash. Flows in and out of the submodel include: i) grain and stover harvested from the farm and purchased from the market, and ii) cash from purchasing and selling grain and stover, hiring labour and income from off-farm work and remittances. Influences in and out of the model include: i) the availability of off-farm work, ii) the availability of labour (both family and hired) for on-farm activities, iii) the hourly wage rate for hired farm labour, and iv) the market price at which grain and stover can be bought and sold.

The household's grain and stover stores are augmented each season when maize is harvested and depleted on a daily basis by the household and their livestock. In order to calculate the household's daily maize requirement, daily maize demand for each household member is based on the suggested calorie intake for their gender and current age derived from the MyPyramid Food Guidance System (Britten et al., 2006) and assuming high levels of activity[13], a calorific value of 365 Kcal per 100 grams of maize (USDA, 2021) and maize constituting 36% of an individual's total food calories (Mohajan, 2014). Daily stover requirement for livestock is calculated by the livestock submodel (see section 2.3.3).

If there is insufficient maize grain or stover in the store to cover the household's needs for the next two weeks, cash from the household's cash store can be used to purchase grain and stover. If there is insufficient cash to cover the household's deficit, a proportion of the household's labour is used to earn off-farm income, reducing the amount of labour available for on-farm activities. Given the unreliability of the rains in our study area, households usually hold on to surplus grain for future household use rather than sell their surplus. The model thus assumes that, after each harvest, the household will only decide to sell grain if they have enough grain

[13] "Active means a lifestyle that includes physical activity equivalent to walking more than 3 miles per day at 3 to 4 miles per hour, in addition to the activities of independent living" (Britten et al., 2006: 584).

in their store to cover their requirement for the next 548 days. Any extra grain is considered surplus, sold and the resulting cash saved.

In our study area, households often receive cash transfers in the form of remittances from family members living elsewhere (e.g., nearby towns or urban centres such as Nairobi and Mombasa). Within the model, if the household has a migrant family member, a small amount of cash is therefore assumed to be received by the household each month for purchasing maize grain and stover.

Household labour is distributed between off-farm work and several on-farm activities depending on the time of year and whether cash is needed. Total labour availability is first calculated for the household, excluding any hired labour. This is based on the total number of adult members (members under 18 are assumed to be in full-time education and thus unavailable) and assuming each adult member spends eight-hours working per day. If cash is needed to buy grain or stover, the household will devote as many hours as available to working off-farm, with the availability of off-farm employment represented as a fraction of the total household labour available. Any remaining labour plus any hired labour is then used for on-farm work as allocated by the crop submodel.

The price at which grain can be purchased and sold (Table 3.1) is based on estimates from community facilitators and varies from 30 Ksh kg^{-1} in times of surplus, up to 100 Ksh kg^{-1} in times of shortage, and around 70 Ksh kg^{-1} during normal times. Times of surplus and shortage were informed by project survey data regarding which months of the year households are typically able to source their food from their farm (i.e., times of surplus) (see Figure S3.2, Appendix 7). Similarly, the price of maize stover is estimated at 1,000 Ksh per donkey cart (approximately 120kg based on Lukuyu *et al.* (2011)). Since maize stover is a critical feed resource during the dry season when other forms of fodder such as Napier grass (*Pennisetum purpureum*) are less available, this price is assumed to increase to 1,200 Ksh per cartload in August and September (Table 3.1).

In order to calculate cash income from off-farm work, time spent working off-farm is multiplied by an hourly wage derived from the monthly basic wage for a general labourer outside of Nairobi as published by the Kenyan Bureau of National Statistics (KNBS 2019). Since the types of off-farm work typically pursued by project households tend to be non-agricultural, the hourly wage rate is assumed not to fluctuate seasonally. The hourly wage rate of hired labour for on-farm work is derived from the official basic wage for an unskilled labourer within the agricultural industry (KNBS 2019) and is assumed to fluctuate seasonally (i.e., hiring labour is more expensive during the rains due to higher demand) (Table 3.1).

Table 3.1 Market price of grain and stover and wage rate for off-farm work and hired labour.

Activity	Calendar months											
	J	F	M	A	M	J	J	A	S	O	N	D
Maize grain price (Ksh kg^{-1})	100	70	30	30	30	30	70	70	70	100	100	100
Maize stover price (Ksh kg^{-1})	8.3	8.3	8.3	8.3	8.3	8.3	8.3	10	10	8.3	8.3	8.3
Wage for off-farm work (Ksh hr^{-1})	30	30	30	30	30	30	30	30	30	30	30	30
Wage for hired labourer (Ksh hr^{-1})	25	28	28	28	28	28	25	25	25	28	28	28

2.3.2 Cropland submodel

The cropland submodel represents the area of land used for growing maize and simulates the effect of several management interventions – the use of planting basins, the application of farmyard manure, inorganic nitrogen fertilizer and management of crop residues. Given that medium sized basins (60x60cm) were the most popular amongst farmers participating in the planting basin planned comparison, we developed our model based on the use of medium sized basins only. While Simile is used to model management activities (e.g., when to plant, how much manure to allocate etc.), the cropland model links to a biophysical APSIM model that simulates soil nutrient and soil water dynamics and subsequent maize yield (see Figure 3.1 and section 2.3 for further details). Flows in and out of the cropland model from other Simile submodels include: farmyard manure from the livestock submodel and grain and stover to the household model.

For simplicity, the total amount of land available for growing maize is set externally as a fixed parameter and does not change over the simulation run. However, the proportion of this area under planting basins can change depending on the amount of labour the household devotes to digging and maintaining their basins. Any land not under planting basins at the onset of the rains is cultivated using the household's usual tillage practice (i.e., ox plough or hand hoe cultivation). In our application of the model, the household has two fields under different management strategies – one with basins and one without. Within APSIM these fields are modelled using two separate maize submodels (using the APSIM-Simile interface, multiple

APSIM crop models can be managed from within Simile as separate fields, each with differing management).

Within the Simile model, available labour is prioritised for certain activities based on a simple decision tree and seasonal calendar (Table 3.2). If there is currently no crop growing and the rains have not yet started (i.e., dry the season), labour is prioritised for digging and maintaining planting basins. The hours an individual household member can spend digging basins each day is specified as a fixed parameter and it is assumed that households will convert 100% of their maize growing area to basins if they have sufficient labour to do so.

Given that the household's basin and non-basin fields are managed concurrently, multiple farming activities can occur at the same time. Each day, available labour is divided equally among activities demanding labour. Once the rains have started, any land not under basins is cultivated using the farmers usual tillage practice. This is then followed by manure and fertilizer application (if available) and planting. For fields with basins, manure and fertilizer application (if available) and planting can start immediately after the onset of the rains. Farmyard manure application depends on manure availability. The household's livestock are the only source of manure on the farm, hence, if the household has no livestock, no manure is applied to their fields. At sowing, accumulated farmyard manure from the livestock submodel is transferred to the crop model and applied to the household's fields evenly across all fields.

Weeding is assumed to be carried out by hand hoeing. Based on our discussions with farmers, we estimated weeding basins takes roughly half the time than in plots cultivated using farmer's usual practice (Crossland et al., 2021). If the maize crop is still alive, weeding in each field occurs 40 days after it was planted. At harvest, each treatment is harvested once the maize crop has matured, and grain and stover immediately transferred out of the submodel to the household's stores. However, if the household does not have livestock, it is assumed that all stover is retained in the field as residue given its role in maintaining soil fertility. Maize grain and stover yield are modelled in APSIM at the plot scale and then scaled to the farm level in Simile based on the area of each treatment.

Given that our aim was to describe the outcomes of management practices and not to predict management decisions, management decisions and labour allocation within the model are not directly influenced by economic performance or returns to labour (e.g., if basins perform well, additional labour is not then allocated to digging more basins).

Table 3.2 Seasonal calendar used to inform model development and scheduling.

Activity	Calendar months											
	J	F	M	A	M	J	J	A	S	O	N	D
Digging basins		■	■				■	■	■			
Repairing basins		■	■				■	■	■			
Land preparation			■	■	■					■	■	■
Sowing window			■	■	■					■	■	■
Weeding	■	■		■	■	■	■			■	■	■
Harvesting period		■				■	■					

2.3.3 Livestock submodel

The livestock submodel describes the household's cattle in terms of their bodyweight, their stover demand, intake, and manure production. Flows in and out of the submodel include stover and manure. While milk from cattle is an important source of household income in the drylands of Kenya and increased offer rates of maize stover during the dry season could in theory help maintain healthy milk yields (Methu et al., 2001), changes in feeding strategy (e.g., use of excess feeding) and milk yields are not considered in this study and instead fixed offer rates are assumed.

Livestock dynamics are similar to those used by van Wijk et al. (2009). Cattle are modelled as discrete animals and are assumed to have a lifespan of 12 years, to be born with a bodyweight of 30 kg and reach a maximum bodyweight after the age of 4.5 years. Once an animal reaches 10 years of age a replacement calf is kept on-farm. This new cow will then grow to a bodyweight of 340 kg over the course of 4.5 years. Cattle are removed from the farm once they reach the end of their lifespan.

The model assumes that cattle are kept in small enclosures (*bomas*) throughout the dry season and at night during the wet season. During the dry season (August-September), maize stover is offered to cattle at a rate of 30g per kg of bodyweight per day (Methu et al., 2001; Rufino, 2008). During the wet season, it is assumed that the household is able to meet their livestock's feed requirement from sources other than maize stover (e.g., Napier grass, pasture and tree fodder) thus stover offer rates are reduced to zero.

Manure is collected from the enclosure daily and stored before being exported to the crop submodel at planting time as farmyard manure. It is assumed that 100% of manure excreted by cattle while they are kept in the enclosure is collected (Rufino, 2008). During the wet season, only 40% of daily excretion is collected since cattle are only kept in the enclosure overnight. While in reality, how manure is stored, its frequency of collection, and an animal's diet can all influence the quality of manure, we assume that all farmyard manure applied to the household's fields has the same chemical composition. However, to account for the loss of dry mass during manure decomposition, the quantity of manure collected each season is reduced by 55% before being exported to the household's fields based on Rufino (2008) and assuming seven months of storage.

2.4 APSIM model development

Soils in smallholder farming systems often suffer from compaction, hardpans and crust formation, leading to poor rainfall infiltration, limited plant root development and high levels of surface run-off (Gitau et al., 2006; Miriti, 2013). Soils with a high clay content, such as those found in our study site (see Figure S3.3, Appendix 7), are particularly vulnerable to such degradation. The physical action of digging basins can help break through these crusted soils and hardpans, increasing water infiltration and deeper percolation, while the basin structures themselves help to reduce and capture surface runoff (Kimaru, 2017). Several studies have shown that rainfall infiltration is significantly higher in basins compared to ploughed fields water (Kimaru, 2017; Rockström et al., 2009). To simulate the degraded soils of our study area and the effect of basins on surface runoff and infiltration, we adjusted several soil parameters within APSIM.

Under degraded, low-input conditions, most rainfall is typically lost as non-productive surface water runoff, evaporation and deep percolation, and the productive proportion of rainfall can be as low as 10% (Rockström et al., 2002). For the non-basin instance of the APSIM crop model, we therefore used a runoff curve number of 90 to reflect high levels of runoff (Mutua et al., 2006). To simulate the effect of crusted soils and the presence of a hardpan, we reduced the rate at which water can percolate through the surface soil layer using the parameter KS and used the root exploration factor (XF) to slow down the advance of the root exploration front through the soil profile (Table 3.3). For the basin instance of the model, we used the default KS and XF values and reduced the runoff curve to 70 (Table 3.3).

Table 3.3 APSIM soil properties for basin and non-basin instances of the model. Values altered from default values highlighted in bold. KS specifies the number of millimetres per day allowed to drain from each layer when soil water is above saturation, Maize root exploration factor (XF) determines the advance of the root exploration front through the soil profile.

Soil depth (cm)	Basin plot		No Basin plot	
	KS (mm/day)	Maize XF (0-1)	KS (mm day^{1})	Maize XF (0-1)
0-15	100.00	1.00	100.00	**0.10**
15-30	100.00	1.00	**10.00**	**0.10**
30-45	100.00	1.00	100.00	**0.50**
45-60	100.00	1.00	100.00	1.00
60-80	100.00	1.00	100.00	1.00
80-100	100.00	1.00	100.00	1.00
100-120	100.00	1.00	100.00	1.00
120-140	100.00	1.00	100.00	1.00
140-170	100.00	1.00	100.00	1.00
170-200	100.00	1.00	100.00	1.00

In the absence of detailed experimental data on the performance of basins, a traditional approach to model validation was not possible. Instead, to check that our adapted APSIM model behaved as expected under a range of rainfall conditions and produced sensible maize yields, we compared simulation output with yield data collected under the planned comparisons (see Chapter 2 for yield data analysis). To do this, we conducted multiple simulation runs using long-term climate data from 1984 to 2018 (Funk et al., 2015; Sparks, 2018) for six sites in Kenya representing an average annual rainfall gradient from 289 to 1973 mm year^{-1}, and soil data sourced from an agricultural research station in Katumani, Machakos County (N. Huth 2020, personal communication). For each site, we ran multiple permutations using different combinations of plant population (3, 4, 5, and 6 plants m^{2}) and nitrogen (N) fertilizer rates (0, 45, 90 and 180 kg N ha^{-1}) so as to emulate variation in farmers management practices. Based on visual comparison (Figure 3.3), our model was found to produce similar yields to those of the planned comparison and displayed a similar yield response with increasing rainfall. The adapted model also resulted in expected trends in terms of surface water runoff, with simulated output showing basin simulation runs to substantially reduce runoff compared to non-basin runs (Figure 3.4).

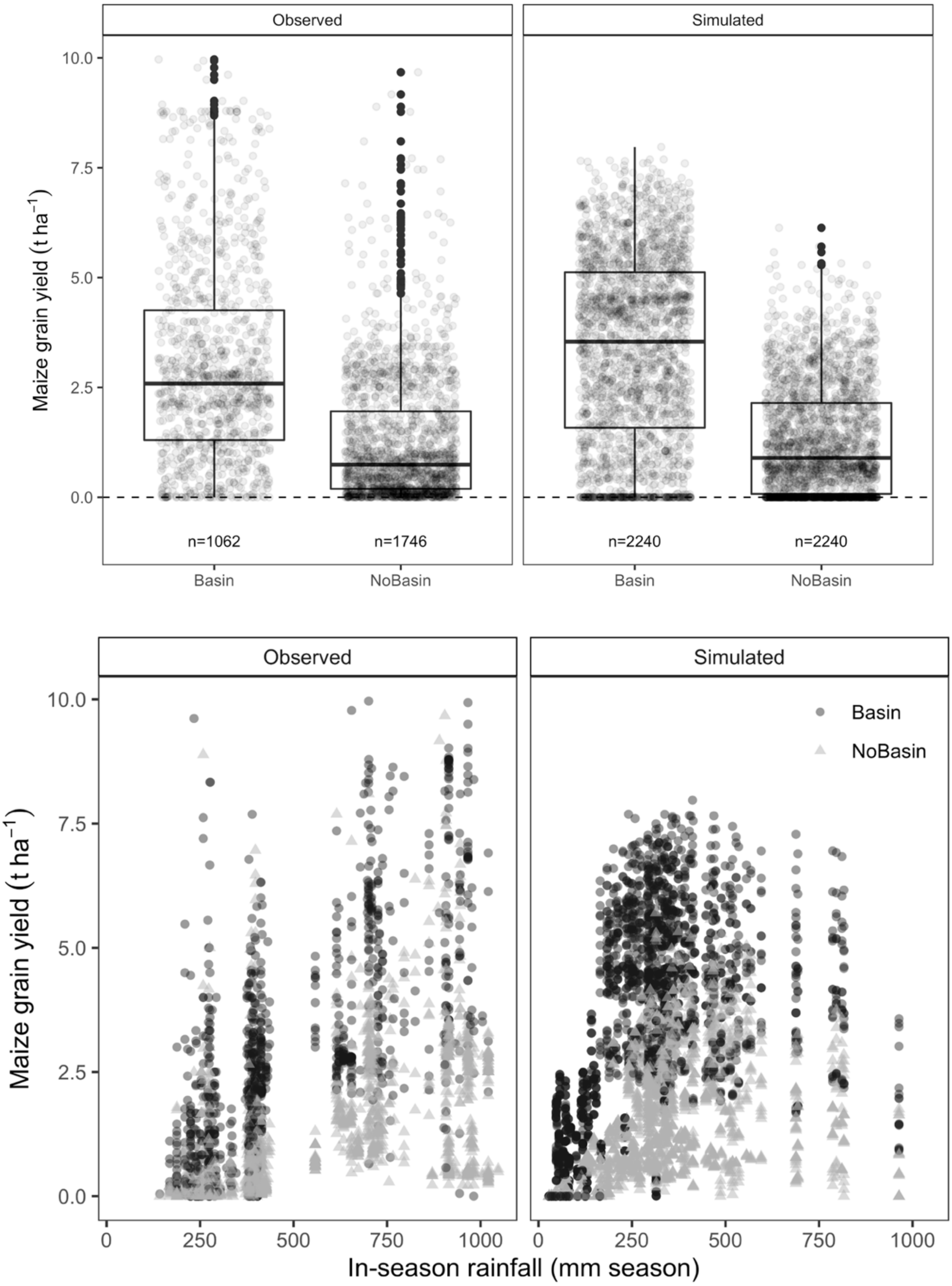


Figure 3.3 Simulated maize grain yields from basin and non-basin plots compared to observed yields from the planting basin planned comparison (top panels) and simulated and observed grain yields against in-season rainfall (bottom panels). Based on visual comparison, simulated yields are similar to observed yields and show a similar response with increasing rainfall.

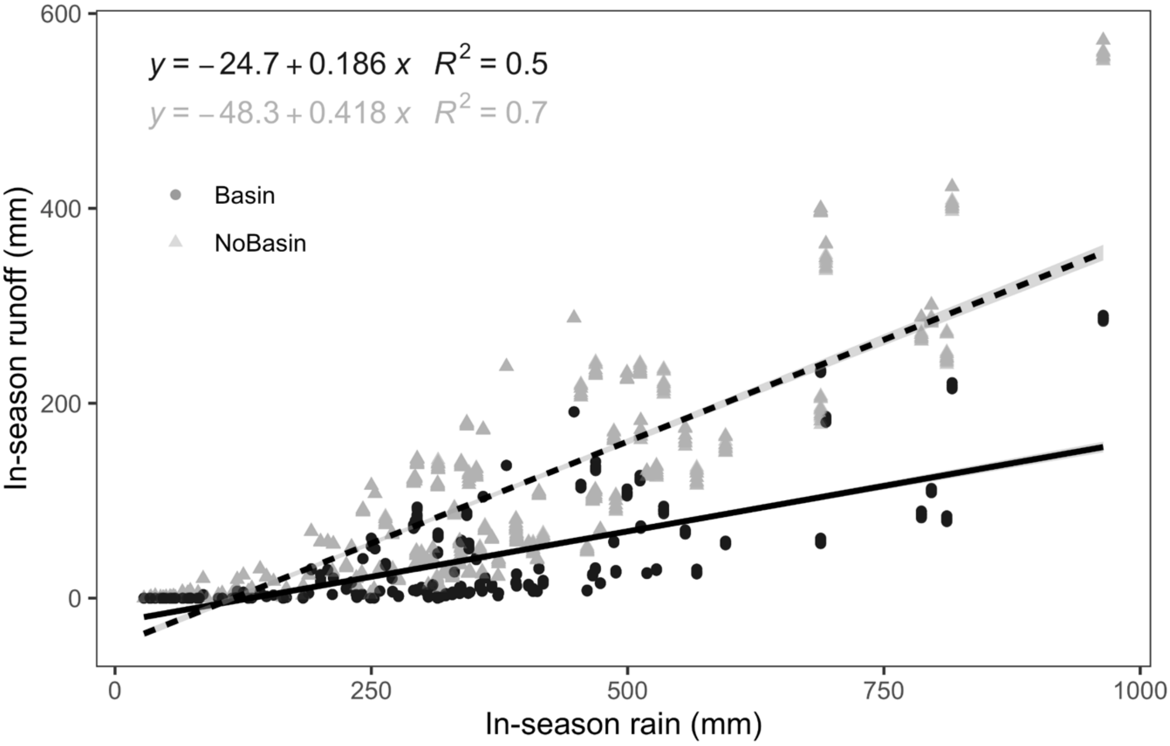


Figure 3.4 Surface water run-off regressed against in-season rainfall for simulation runs with and without basins and using data from sites located across a rainfall gradient in Kenya. The simulation model resulted in expected trends in terms of surface water runoff, with basin simulation runs to substantially reduce runoff compared to non-basin runs.

2.5 Simulation set-up and scenarios

In our final application of the model, the APSIM biophysical model was parameterised to represent agroecological conditions in Kibwezi East, Makueni County. We chose this site based on the availability of soil data for improving model parameterisation. To set-up the APSIM soil submodel, we first extracted base characteristics for soils in our study from SoilGrid™ (Poggio et al., 2021) (available to download through the APSIM platform). We then adapted several parameters based on soil data collected in our study site (L. Winowiecki 2020, personal communication) using the Land Degradation Surveillance Framework (LDSF) (Vågen et al., 2010). This data included soil pH, soil organic carbon and total nitrogen content (see Table S3.2, Appendix 7 for values used to parameterise APSIM soil submodel).

Kibwezi East also has the driest climate out of the six sub-counties the project was working in and a high prevalence of soil degradation (Table 2.2 and 2.2, Chapter 2). Farmers in this site are thus likely to benefit from the use of basins, as reflected by the large numbers of farmers participating in the planting basin planned comparison and the impressive average yield response to basins in this site (see Figure 2.10 and 2.11, Chapter 2). To explore the longer-term performance of planting basins, we selected a 20-year period (2000 to 2019) over which to run our model. This time period was chosen based on simulated historical rainfall data sourced from CHRIPS to cover both good and poor rainfall seasons (Figure 3.5), allowing us to examine the performance of basins under a range of rainfall conditions.

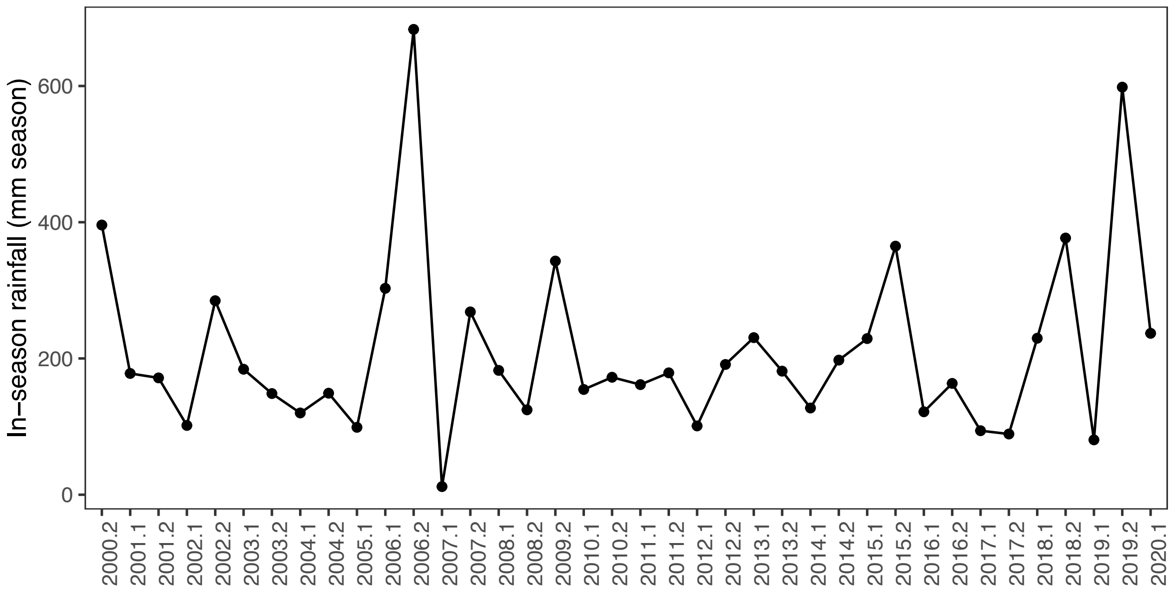


Figure 3.5 In-season rainfall for Kibwezi East 2000-2020 sourced from CHIRPS rainfall data (Funk et al., 2015). For each year, the March-April-May (MAM) season is denoted by '1', the October-November-December (OND) season by '2'.

To validate the utility of APSIM-Simile integrated models in providing context-specific recommendations, we then parameterised the model for two separate households participating in the basin planned comparison in Kibwezi East (Table 3.4). These two households were purposely selected to represent households with contrasting resource endowment based on farm size, number of cattle owned and access to the use of a plough: a lower resource endowed household (LRE household) and a higher resource endowed household (HRE household). Scenario selection took a two-staged approach. For each household, we first used the model to explore what would be needed to increase total grain production over the 20-year period by

30% using various combinations of plant population and N fertilizer rates, both with and without planting basins. We chose a target increase of 30% on the basis that many households in the study area experience a three-month hunger period between September and December each year (see Figure S3.2, Appendix 7). A 30% increase in total grain production is thus likely to make a meaningful contribution to closing this hunger gap or, should a household already be relatively self-sufficient, a substantial contribution to income through the sale of surplus grain. Based on these initial simulation runs and what was needed to increase production by 30%, we then selected several scenarios for each household to explore and compare in more detail (see the results section for description of final scenarios).

Scenario analysis involved assessing a range of plot and farm level indicators to compare the annual performance of each intervention compared to the baseline. Production and socio-economic indicators included production and self-provision of maize grain and stover, resource use efficiency, profitability, and income per capita. Several biophysical indicators were also selected to assess the sustainability of each scenario, including change in soil organic carbon (SOC) stores and surface water run-off. Model outputs were exported from the APSIM-Simile integrated model and all descriptive statistics and data visualisation conducted in R, version 4.0.3 (R Core Team, 2020).

Table 3.4 Characteristics of the two selected households (variables highlighted in bold used in model parameterisation).

	Lower Resource Endowed Household	**Higher Resource Endowed Household**
Household characteristics		
Gender of project farmer	Female	Female
Gender of household head	Female	Male
Marital status	Divorced	Married
Household size	5	5
Adults (gender and age)	Female (42) Male (28) female (26)	Male (50) Female (45)
Children (gender and age)	Male (8) Female (6)	Male (10) Female (8) Female (6)
Number of active adult members	2	2
Land per household member (ha)	0.2	0.4
Distance to market (km)	4	1
Hired labour	No	No
Remittances	No	No
Quality of housing	Semi-permanent	Permanent
Farm size (ha)	1	2
Cultivated area (ha)	0.5	1
Livestock (cattle)	None	2 cattle (5 years & 10 years)
Cultivation method	Hand hoe cultivation	Ox plough cultivation
Farmyard manure	No	Yes
Inorganic fertilizer	No	No
Crop residue removed	50%	100%

3. Results

We first used the model to explore, for each household, what would be needed to increase total grain production over the 20-year period by 30% using various combinations of plant population and N fertilizer rates, both with and without planting basins (Figure 3.6). For the HRE household, these initial simulation runs showed that using N fertilizer and increasing plant population without the use of planting basins had a limited or even negative effect on total grain production (Figure 3.6 – top panel). This likely reflects interaction effects between nitrogen application, plant population and water availability. When water availability limits plant growth – as is often the case in the drylands – plants require additional water to make use of any additional nitrogen; using planting basins increases soil water availability and thus relieves this constraint.

In contrast, for the LRE household, using N fertilizer and higher plant population rates, even without basins, had a positive effect on total grain production. An increase in production of 30% was possible with population rates over 3.5 plants m^2 and N application rates of 20 kg ha^{-1} or higher. This is because, unlike the HRE household, the LRE household does not own cattle nor do they apply farmyard manure to their fields. Nitrogen availability thus limits yield even when basins are not used. For both households, increasing total production by 30% was possible when using basins, even without the use of N fertilizer and increased plant population (Figure 3.6 – bottom panel). However, the number of basins the HRE household required for a 30% increase was higher than that needed by the LRE household. When N fertilizer was applied, the number of basins needed dropped dramatically for both households, with rates of 10kg and 20 kg N ha^{-1} resulting in the largest production gains.

Based on these initial simulation runs and what was needed to increase production by 30%, we selected four scenarios for each household (eight scenarios in total) to explore in a more detailed comparison (Table 3.5, Figure 3.7): two low input scenarios without the use of N fertilizer, both with and without basins (i.e. baseline and basins only), and two higher input scenarios with the use of N fertilizer (and increased plant population if needed to achieve a 30% increase), both with and without basins (i.e., baseline + N and basins + N). Since we were unable to increase total production for the HRE household by 30% without the use of basins, we chose the non-basin option providing the largest production gain (i.e., 4.5 plants m^2 and 10kg N ha^{-1}).

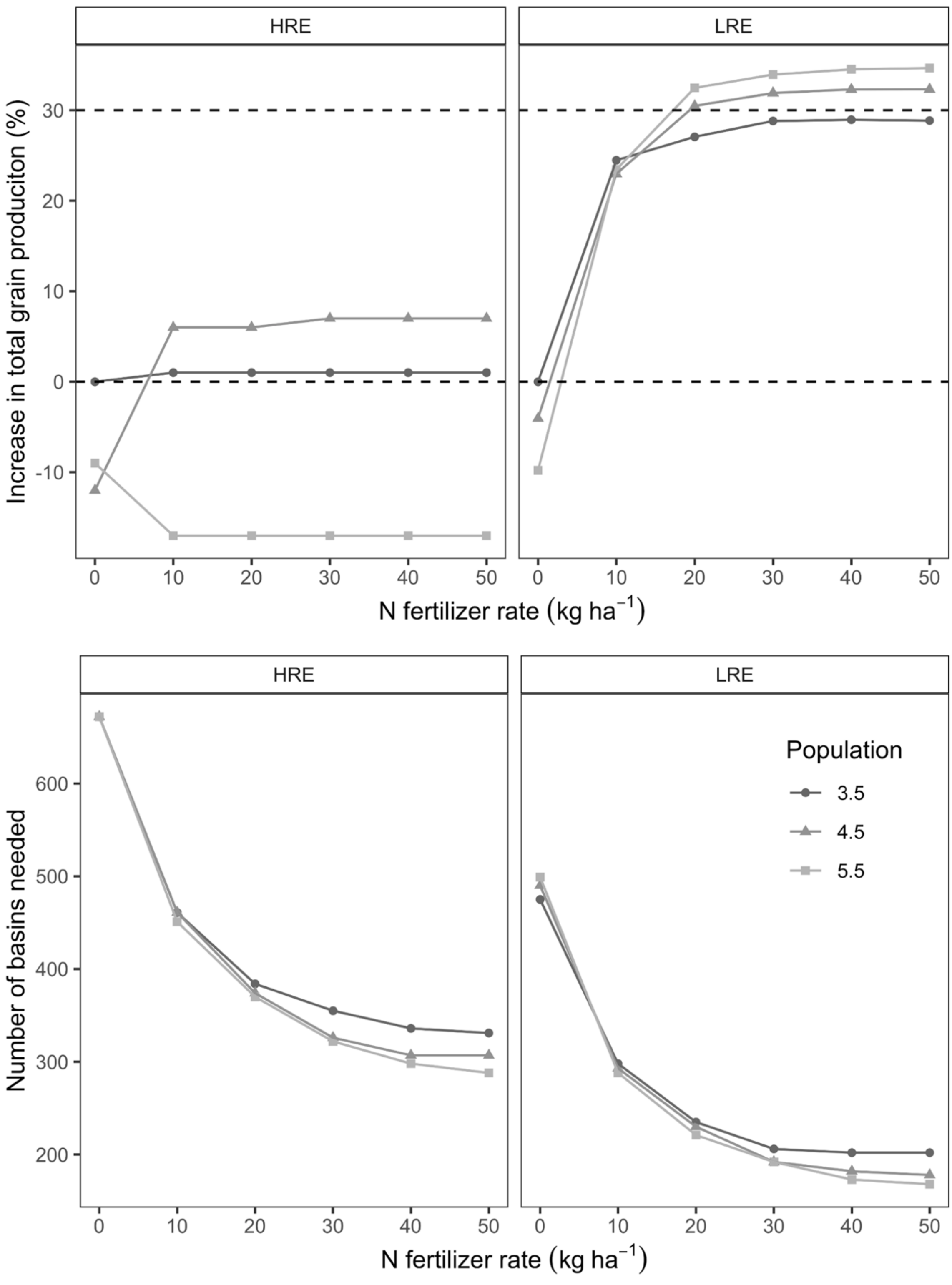


Figure 3.6 Top panel: Percentage increase in total grain production over a 20-year simulation compared to baseline under different rates of N fertilizer application and plant populations and no planting basins. Increasing N application had a greater yield effect on yield for the lower resource endowed (LRE) household because, unlike the higher resource endowed (HRE) household, they do not apply any manure to their fields. Bottom panel: Number of basins needed

to increase total grain production by 30% under different N and plant population rates. For both households, the number of basins needed decreased with the application of N fertilizer and to a lesser extent increased plant population.

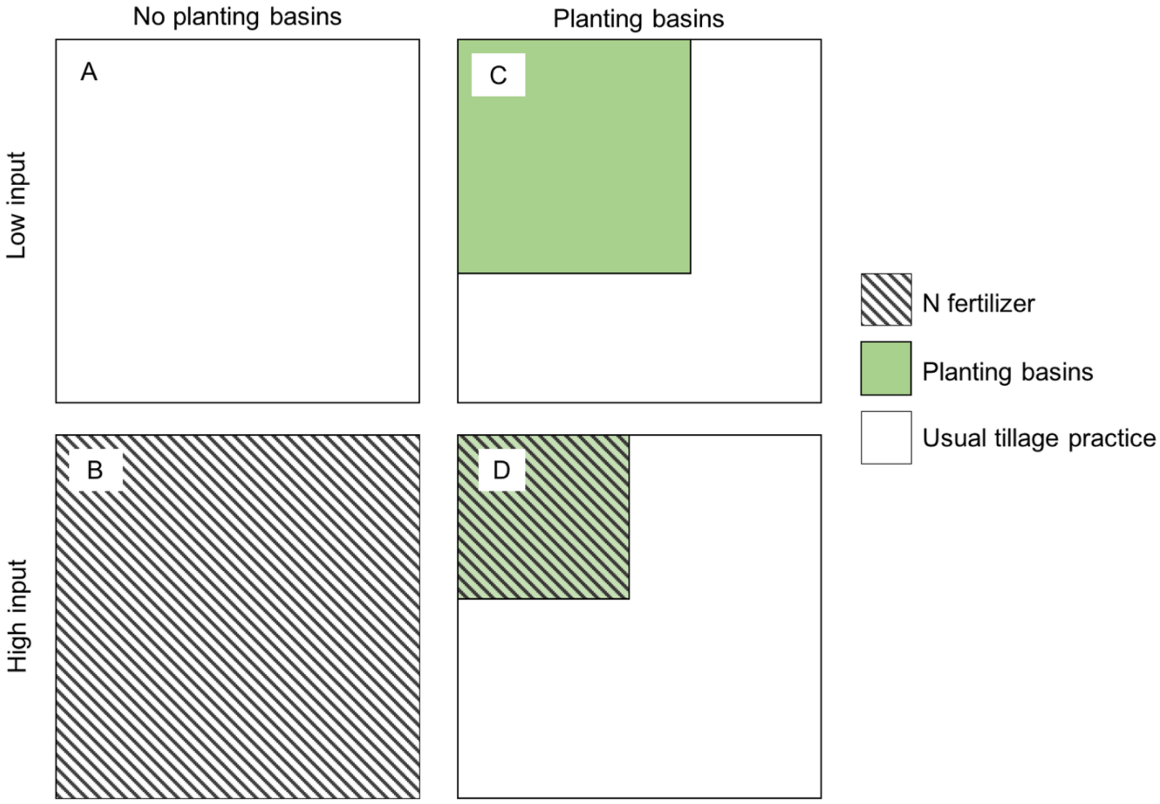


Figure 3.7 Example configurations of the four scenarios explored for both households: A) baseline scenario where farmer's usual farming practice is used over their total maize area (i.e., low plant population and no N fertilizer applied); and three intervention scenarios: B) Baseline plus N fertilizer rate needed to increase baseline production by 30% (plus increased plant population if required); C) Area of basins needed to increase baseline production by 30% without the use of N fertilizer; and D) Area of basins plus N fertilizer rate (i.e., 20 kg N ha^{-1}) needed to increase baseline production by 30%.

Table 3.5 Final scenarios explored for each household based on what is needed to increase total grain production over the 20-year simulation run by 30 percent compared to baseline by means of using N fertilizer (and increase plant population if needed) and/or planting basins.

	Scenario			
	Baseline (low input, no basins)	**Baseline+N** (high input, no basins)	**Basins** (low input, basins)	**Basins+N** (high input, basins)
Lower resource endowed household				
Number of planting basins on farm	---	---	475	235
Area under planting basins (ha)	---	---	0.068	0.034
% of cultivated area under basins	---	---	13.67	6.77
% of farm under basins	---	---	6.84	3.39
N application rate – basin plot (kg ha^{-1})	---	---	---	20
N application rate – farmer practice plot (kg ha^{-1})	---	20	---	---
Plant population – basin plot (plants m^2)	---	---	3.5	3.5
Plant population – farmer practice plot (plants m^2)	3.5	4.5	3.5	3.5
Higher resource endowed household				
Number of planting basins on farm	---	---	672	384
Area under planting basins (ha)	---	---	0.097	0.055
% of cultivated area under basins	---	---	9.68	5.50
% of farm under basins	---	---	4.85	2.75
N application rate – basin plots (kg ha^{-1})	---	---	---	20
N application rate – farmer practice plots (kg ha^{-1})	---	10	---	---
Plant population – basin plot (plants m^2)	---	---	3.5	3.5
Plant population – farmer practice plot (plants m^2)	3.5	4.5	3.5	3.5

3.1 Maize production and self-sufficiency

In terms of total grain production over the 20-year run, the LRE household was able to produce 76% of their household's total grain demand under the baseline scenario (Table 3.6). Under the three intervention scenarios (i.e., baseline+N, basins-only, basins+N), grain production increased to 96% of the household's demand. For the HRE household, total grain production exceeded total demand under all scenarios, even baseline, ranging from 140-183% of total grain demand. For both households, all intervention scenarios increased the total amount of grain sold compared to baseline. This increase in sales was largest under the baseline+N scenario, especially for the LRE household. The two basin scenarios, however, provided the largest reductions in the amount of grain purchased from market. This reduced reliance on market bought grain is also illustrated in Figure 3.8 which shows the quantity of grain in the household's stores over the simulation run. Based on total production alone, we might conclude the HRE household to be maize self-sufficient (i.e., total production exceeds total consumption) and the LRE household to be maize insecure under baseline conditions but almost self-sufficient under the intervention scenarios. However, these total grain production values conceal considerable inter-annual variation in production and do not necessarily mean households produced sufficient nor surplus grain each year.

Table 3.6 Total values over the total 20-year simulation run for each scenario and household.

	Scenario			
	Baseline	**Baseline+N**	**Basins**	**Basins+N**
Lower resource endowed household				
Total grain consumed (kg)	8,850	8,850	8,850	8,850
Total grain produced (kg)	6,533	8,525	8,510	8,487
Total grain bought (kg)	3,239	3,215	1,550	1,695
Total grain sold (kg)	367	2,335	655	778
% change in grain total production	---	30	30	30
% of total grain demand produced	74	96	96	96
Total stover consumed (kg)	---	---	---	---
Total stover produced (kg)	3,843	5,144	4,186	4,353
Total stover bought (kg)	---	---	---	---
Total stover sold (kg)	3,843	5,144	4,186	4,353
% of total dry season stover demand produced	---	---	---	---
% change in total stover production	---	34	9	13
Higher resource endowed household				
Total grain consumed (kg)	8,785	8,785	8,785	8,785
Total grain produced (kg)	12,334	13,103	16,086	16,003
Total grain bought (kg)	2,600	3,474	435	537
Total grain sold (kg)	5,594	7,590	7,181	7,203
% change in grain total production	---	6	30	30
% of total grain demand produced	140	149	183	183
Total stover consumed (kg)	98,097	99,813	86,735	86,736
Total stover produced (kg)	15,123	17,576	16,715	17,029
Total stover bought (kg)	83,147	82,380	70,124	69,861
Total stover sold (kg)	---	---	---	---
% of total dry season stover demand produced	15	18	19	20
% change in total stover production	---	16	11	13

In terms of annual grain production compared to baseline, we see considerable variation in scenario performance (Figure 3.9 and Table S3.3, Appendix 7). For both households, the baseline+N scenario provided large gains in grain production in years experiencing exceptionally high rainfall (i.e., years 18 to 20), but depressed production in those experiencing low rainfall (i.e., years 10-15). This was particularly pronounced for the HRE household since they already apply farmyard manure and, as previously discussed, any additional nitrogen is likely to have limited benefit and may even delay planting (e.g., family labour used to earn off-farm income to pay for N fertilizer). In contrast, the basin scenarios provided modest gains in most years and showed greater inter-annual yield stability, especially during low rainfall years (i.e., years 10 to 15). Compared to the basins-only scenario, combining basins with N fertilizer application provided some marginal production gains in good rainfall years and helped further reduce year-to-year variation in production over the 20-year run.

For both households, basin scenarios increased the number of years in which they harvested sufficient grain to cover their annual demand (Figure 3.10), and the average days per year they were able to meet their daily grain and stover demand (Table 3.7). For both households, the basins-only scenario provided a slightly higher median number of days compared to the basins+N scenario. In contrast, the baseline+N did not increase the average number of days per year the LRE Household was able to meet its daily grain demand, and even reduced the number of days for the HRE household by an average of 30 days. Basin scenarios also reduced the risk of complete crop failure during poor rainfall years (i.e., years 6 and 17). Although grain production was still very low for these years, households were able to harvest at least some grain rather than none at all. The baseline+N scenario, on the other hand, provided no protection against crop failure, and even increased the number of crop failures experienced by the HRE household. Basin scenarios thus provided greater benefit in terms of improved household food self-provision.

Stover production showed similar trends to grain production, with the baseline+N scenario providing large gains in some years and large losses in others, and the basin scenarios providing more reliable yields (Figure 3.9 and Table S3.4, Appendix 7). Nevertheless, compared to grain production, stover production still benefited from N fertilizer application even in low rainfall years, particularly for the LRE household. For instance, in some years, the baseline+N scenario reduced grain production but increased stover production compared to baseline (i.e., years 10 to 14), and the basins+N scenario often outperformed the basins-only scenario in terms of stover production but not grain production (i.e., in years 10-12). Similarly, in terms of total stover production over the 20-year run, the baseline+N scenario provided the largest increase in total stover production, increasing baseline production by 34% and 16% for the LRE and HRE household, respectively (Table 3.6).

Such findings suggest that even when N fertilizer application has no effect on grain production its application can still provide benefit in terms of increased biomass and stover production. As illustrated by Table 3.6, increases in total stover production under the three intervention scenarios translated directly in to increased stover sales and cash income for the LRE household (since they do not own cattle and all harvested stover is sold), while for the HRE household, increased stover production provided a small contribution to meeting their cattle's stover demand and reducing reliance on stover purchased from market (Table 3.6 and 3.7).

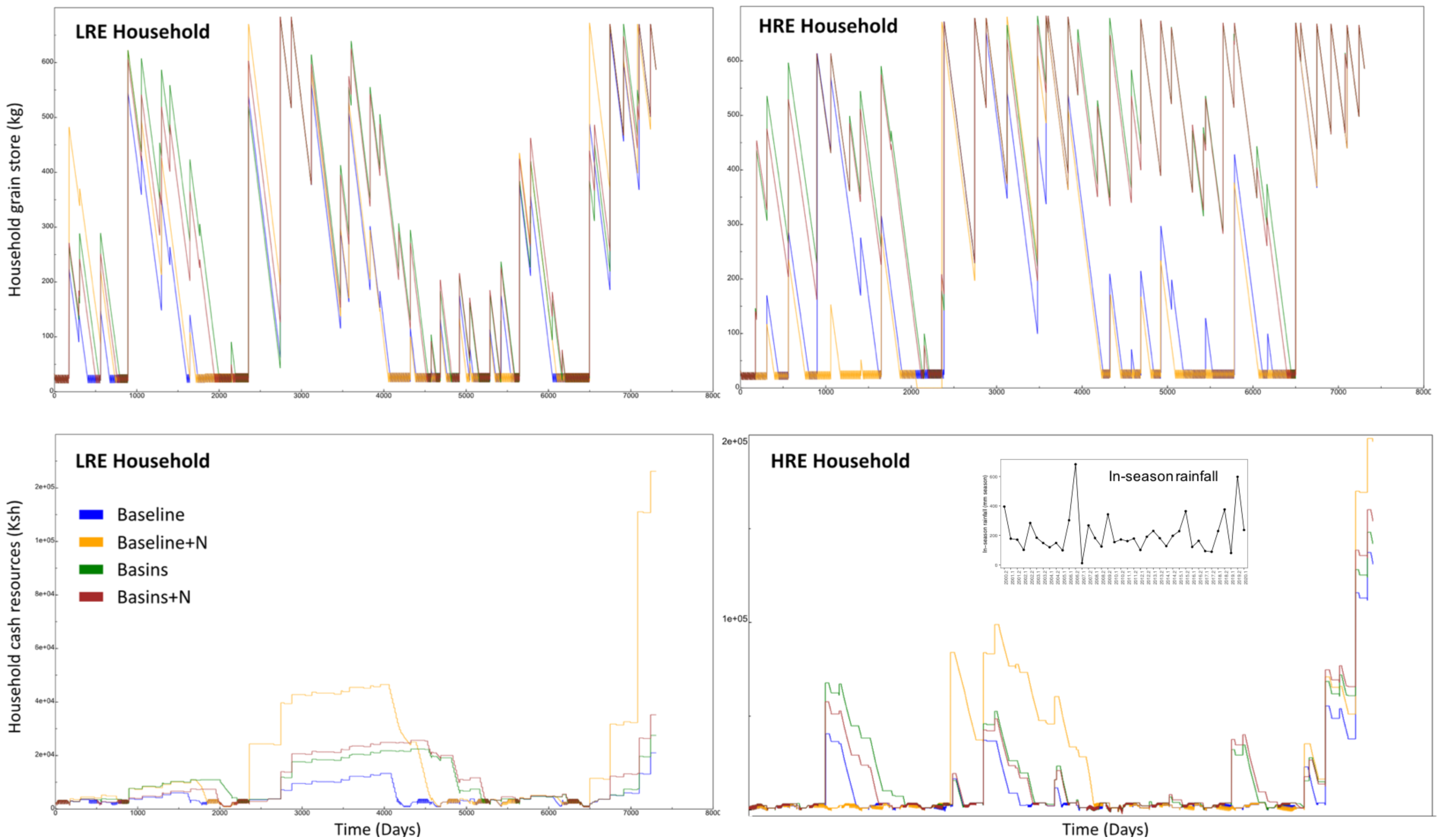


Figure 3.8 Household grain (top panels) and cash reserves (bottom panels) over the 20-year simulation run for each scenario. (Note: regular reliance on grain bought from the market and daily income from off-farm work appear as thick lines close to the x-axis).

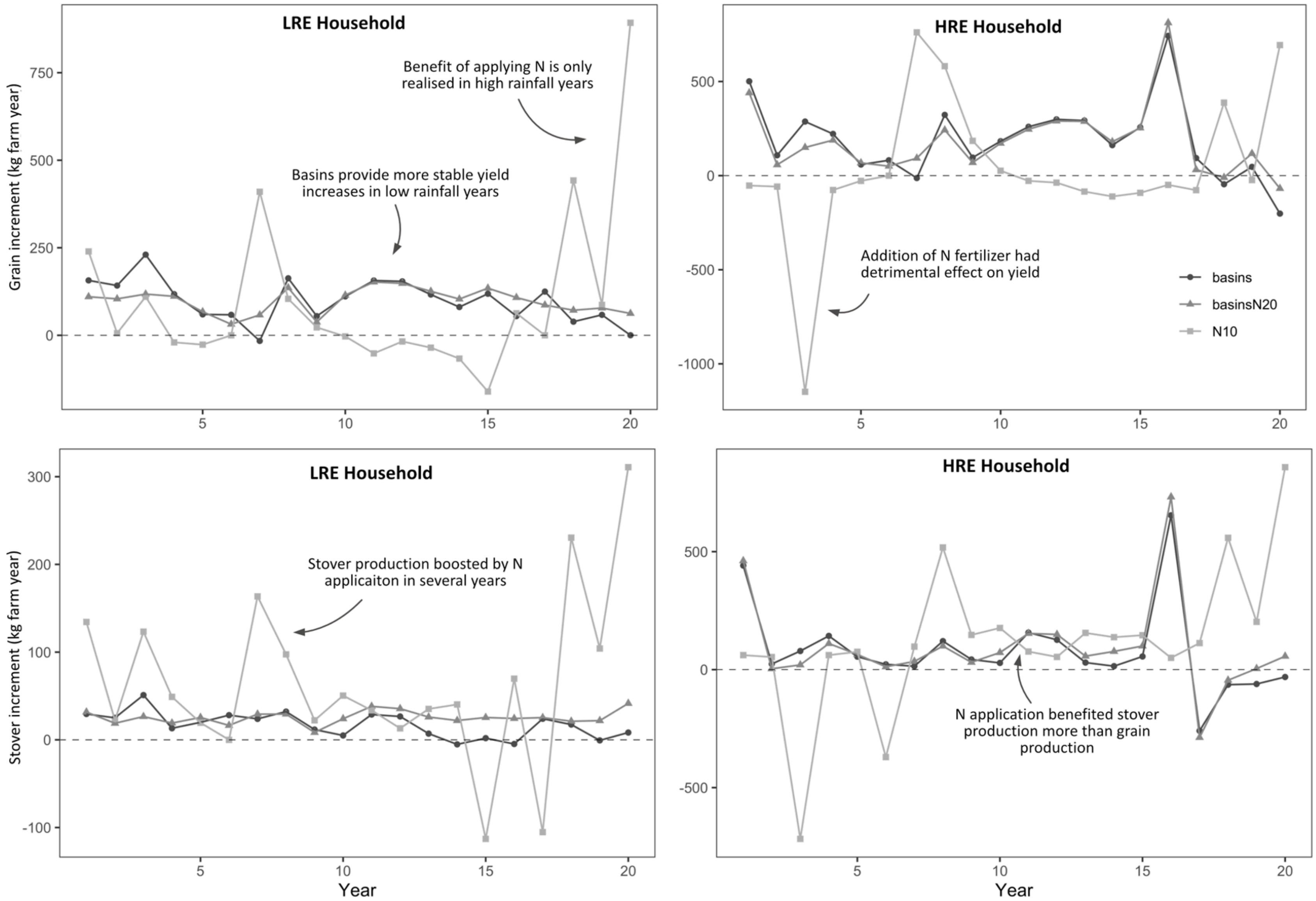


Figure 3.9 Difference in annual on-farm grain and stover production compared to baseline over the 20-year simulation run for the LRE household (left panels) and the HRE household (right panels) scenarios (see Table S3.3 and S3.4, Appendix 7 for average annual values).

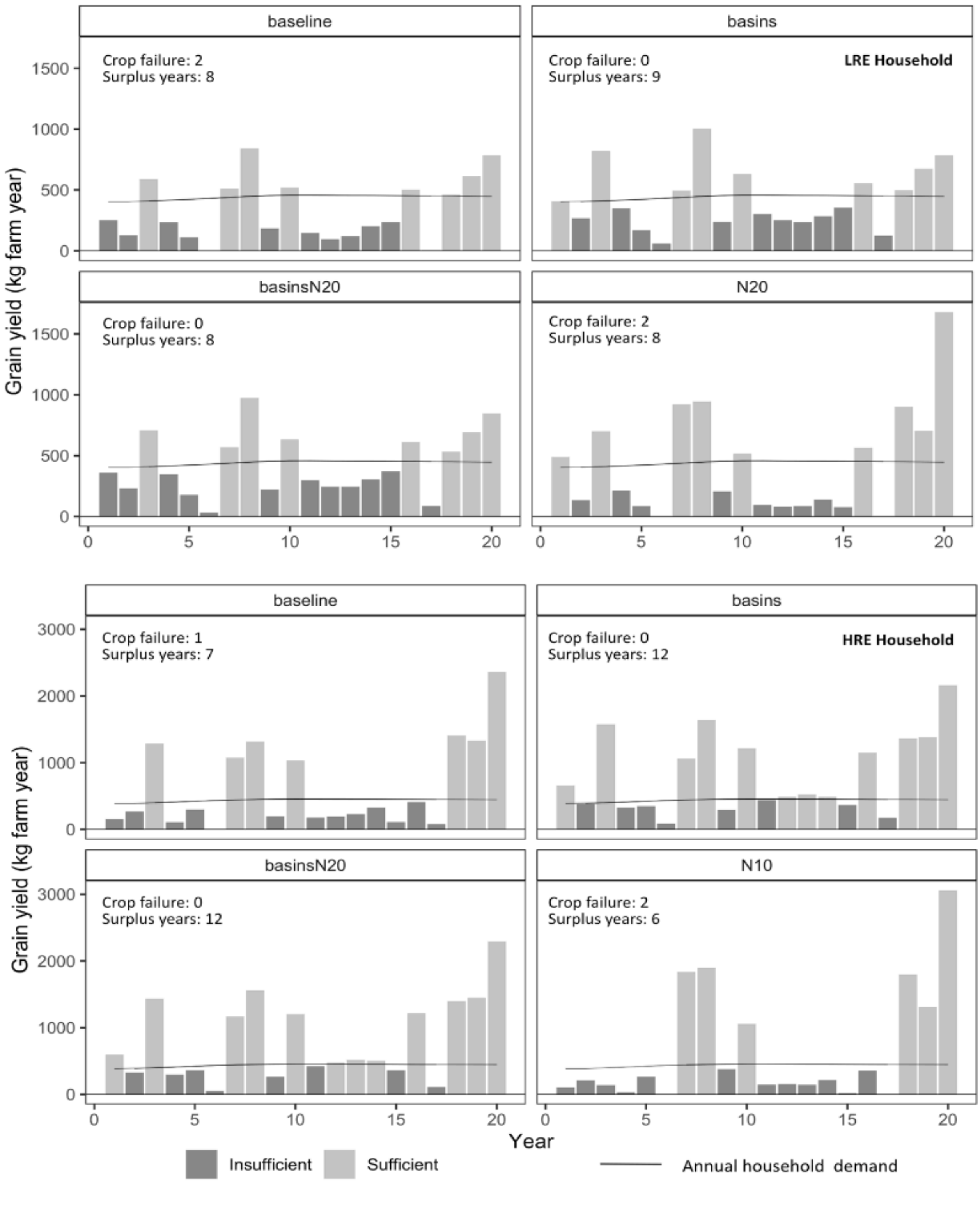


Figure 3.10 Annual maize grain production (kg farm year^{-1}) under each scenario for the lower resource endowed (LRE) household (top four panels) and higher resource endowed (HRE) household (bottom four panels). Solid line displays the annual household maize requirement as members age over the simulation run.

Table 3.7 Additional days of maize grain and stover self-provision compared to baseline.

	Scenario		
	Baseline+N	**Basins**	**Basins+N**
Lower resource endowed household			
Additional days of grain	0 (-131, 360)	95 (-13, 187)	88 (26, 124)
Additional days of stover	---	---	---
Higher resource endowed household			
Additional days of grain	-30 (-938, 622)	149 (-37, 606)	140 (-8, 663)
Additional days of stover	9 (-60, 72)	3 (-22, 55)	5 (-24, 62)

Statistics presented: Median (Range)

3.2 Resource use efficiencies

On average, only the basin scenarios (both with and without N fertilizer) provided gains in resource use efficiencies compared to baseline, producing more grain per hectare, kilogram of nitrogen, millimetre of rain and days of labour, than both baseline and baseline+N scenarios (Table 3.8). For the LRE household, combining basins with N fertilizer was more efficient than using N fertilizer alone, and produced, on average, 257 kg more grain per kg of N applied, an increase in efficiency of over 1500%. For the HRE household, however, nitrogen-use efficiency was greatest under the basin-only scenario, presenting a 46% increase in efficiency compared to baseline. On average, the baseline+N scenario had a negative or no effect on resource use efficiency and, again, showed large inter-annual variability (i.e., extreme increases and decreases in efficiencies). Basin scenarios also provided greater rainwater use efficiency (i.e., more crop per drop) than non-basin scenarios, especially under lower rainfall conditions (Figure 3.11).

Table 3.8 Resource use efficiencies in grain production (i.e., amount of grain (kg) produced per unit of input) for land, labour, nitrogen, and in-season rain.

	Scenario			
	Baseline	**Baseline+N**	**Basins**	**Basins+N**
Lower resource endowed household				
Land productivity (kg ha^{-1})	740.0 (0.0, 2,666.2)	651.6 (0.0, 2,996.8)	1,112.7 (185.7, 3,183.0)	1,093.4 (100.3, 3,097.1)
Within-year difference	---	0.0 (-509.8, 1,404.6)	369.6 (-50.9, 731.0)	342.3 (100.3, 483.2)
Labour productivity (kg person-days^{-1})	6.5 (0.0, 28.4)	5.9 (0.0, 51.1)	7.9 (2.1, 23.3)	8.6 (1.7, 25.4)
Within-year difference	---	0.0 (-3.0, 24.6)	1.4 (-15.0, 4.0)	1.7 (-7.6, 3.9)
Nitrogen use efficiency (kg N kg^{-1})	---	16.9 (6.3, 146.2)	---	273.5 (46.7, 840.1)
Within-year difference	---	---	---	---
Rain use efficiency (kg ha mm^{-1})	2.9 (0.0, 51.5)	2.9 (0.0, 54.1)	6.0 (0.0, 121.2)	8.1 (0.0, 227.0)
Within-year difference	---	0.0 (-2.0, 6.3)	6.1 (-0.2, 25.4)	7.6 (1.2, 61.2)
Higher resource endowed household				
Land productivity (kg ha^{-1})	851.2 (2.3, 4,468.9)	665.8 (0.0, 6,021.1)	1,554.0 (259.0, 5,199.7)	1,604.1 (158.9, 4,943.9)
Within-year difference	---	-118.1 (-3,645.7, 2,416.6)	580.8 (-145.4, 2,357.8)	545.7 (-31.2, 2,578.1)
Labour productivity (kg person-days^{-1})	4.8 (0.0, 41.5)	3.5 (0.0, 54.2)	6.4 (1.5, 31.0)	6.8 (1.1, 35.2)
Within-year difference	---	-0.7 (-15.5, 22.5)	1.3 (-13.6, 5.0)	1.1 (-7.4, 6.7)
Nitrogen use efficiency (kg N kg^{-1})	45.2 (0.1, 372.0)	12.7 (0.0, 161.2)	66.2 (11.5, 357.3)	48.0 (6.1, 277.7)
Within-year difference	---	-29.0 (-210.8, -9.8)	29.4 (-14.7, 133.2)	0.8 (-94.2, 92.0)
Rain use efficiency (kg ha mm^{-1})	2.3 (0.0, 23.4)	2.0 (0.0, 55.2)	6.1 (0.0, 140.8)	7.7 (0.0, 215.6)
Within-year difference	---	-0.4 (-2.4, 26.4)	5.9 (-2.4, 40.4)	7.7 (-0.7, 68.2)

Statistics presented: Median (Range)

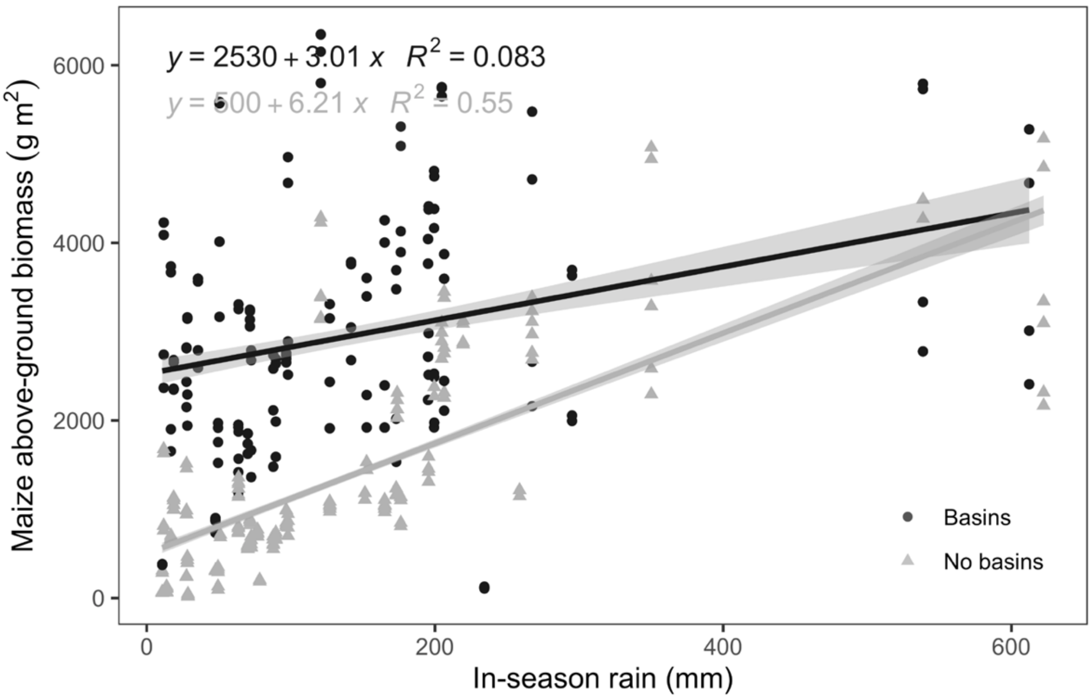


Figure 3.11 Above-ground maize biomass for both basin and non-basin scenarios, regressed against in-season rainfall. Basin scenarios provided greater rainwater use efficiency (i.e., more crop per drop) than non-basin scenarios, especially under lower rainfall conditions.

3.3 Profitability and income

In terms of average gross margin (i.e., value of produce minus the cost of production), grain production was the least profitable under the baseline+N scenario and most profitable under the basins+N scenario (Table 3.9). Although basin scenarios more than doubled average gross margins, these increases were small in absolute terms and translated into only marginal increases in personal daily income (PDI) at the household level. The basins+N scenario, for instance, increased PDI by an average of only \$0.07 and \$0.12[14], for the LRE and HRE household, respectively. Once again, we also saw large inter-annual variability in performance with the baseline+N scenario providing the largest annual increase and decrease in PDI, at -\$1.15 and \$1.12, respectively, while the basin scenarios provided more stable returns. In terms of household cash reserves (Figure 3.8), basin scenarios were able to extend the length of time households had cash available following good rainfall years, especially in the case of the LRE households. This cash was then used to purchase maize from the market in times of need (e.g., during poor rainfall years). Nevertheless, despite households ending

[14] Base on International Comparison Program (ICP) benchmark PPP 2017 for household's final consumption expenditure (World Bank, 2020).

all simulation runs with a sizable cash reserve, it would seem unlikely that any of the scenarios we explored will result in substantial long-term savings and cash accumulation for either household given long-term rainfall variability and the costs associated with poor rainfall conditions.

Table 3.9 Profitability, gross margin and returns to land and labour for each scenario.

	Scenario			
	Baseline	**Baseline+N**	**Basins**	**Basins+N**
Lower resource endowed household				
Gross margin (Ksh farm year)	4,796 (-7,317, 46,714)	181 (-8,707, 63,947)	8,029 (-4,442, 52,491)	9,665 (-5,196, 52,455)
Within-year difference	---	-142 (-6,835, 29,910)	3,233 (-4,564, 15,975)	5,041 (717, 8,163)
Personal daily income (Ksh capita day)	2.6 (-4.0, 25.6)	0.1 (-4.8, 35.0)	4.4 (-2.4, 28.8)	5.3 (-2.8, 28.7)
Within-year difference	---	-0.1 (-3.7, 16.4)	1.8 (-2.5, 8.8)	2.8 (0.4, 4.5)
Returns to labour (Ksh/person-day)	133 (-630, 1,889)	5 (-644, 3,549)	179 (-148, 1,212)	235 (-273, 1,330)
Within-year difference	---	-12 (-228, 1,660)	61 (-1,092, 482)	99 (-559, 358)
Higher resource endowed household				
Gross margin (Ksh farm year)	4,226 (-9,220, 96,299)	930 (-12,447, 131,855)	13,729 (-11,131, 106,666)	16,339 (-12,348, 103,389)
Within-year difference	---	-1,277 (-86,110, 83,651)	8,666 (-8,921, 57,349)	9,081 (-10,138, 63,609)
Personal daily income (Ksh capita day)	2.3 (-5.1, 52.8)	0.5 (-6.8, 72.2)	7.5 (-6.1, 58.4)	9.0 (-6.8, 56.7)
Within-year difference	---	-0.7 (-47.2, 45.8)	4.7 (-4.9, 31.4)	5.0 (-5.6, 34.9)
Returns to labour (Ksh/person-day)	80 (-272, 1,423)	24 (-662, 3,891)	194 (-216, 1,307)	253 (-271, 1,406)
Within-year difference	---	-29 (-1,261, 2,469)	39 (-623, 660)	79 (-284, 806)

Statistics presented: Median (Range)

3.4 Returns to labour

Figure 3.12 compares annual returns to labour under each scenario with the average wage rates for different off-farm occupations, ranging from working as a local agricultural labourer to a skilled artisan working in Nairobi (KNBS, 2019). Despite basins requiring more labour per hectare than farmers usual tillage practices, only the basin scenarios provided average returns to labour similar to that of working as a local agricultural labourer. For both households the non-basin scenarios, on average, performed much worse, with the baseline+N scenario almost failing to break even. Nevertheless, we again saw large variation in scenario performance reflecting variability in rainfall conditions. In some years, all four scenarios provided labour returns greater than the average wage for a highly skilled labour in Nairobi, while in other years, they failed to provide a positive return at all. Again, this variability was greatest for the non-basin scenarios, especially the baseline+N scenario, given the strong dependence of their performance on rainfall conditions.

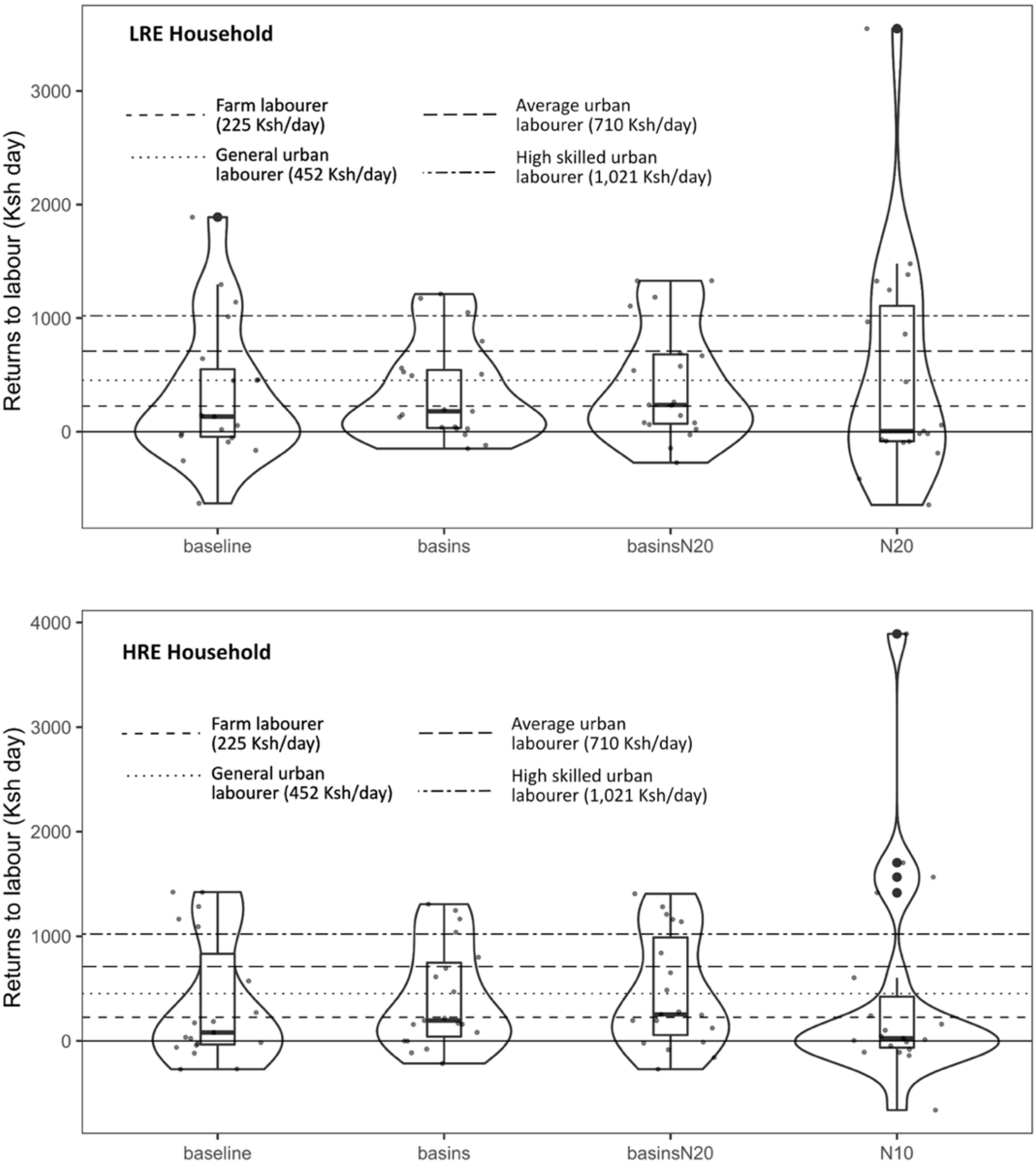


Figure 3.12 Annual returns to labour by scenario for the LRE household (top panel), and the HRE household (bottom panel). Horizontal lines show average wage rate for different occupations (KBNS, 2019), to allow for easy comparison and to assess whether the system will be attractive to family members compared to off-farm work or whether it would justify hiring labour. Despite basins

requiring more labour per hectare than farmers usual tillage practices, only the basin scenarios provided average returns to labour similar to working as a local agricultural labourer.

In order to maintain the number of basins required to increase total production by 30% under the basin, the LRE and HRE household spent roughly 59 and 84 minutes per day during the dry season (approximately 120 days per year – the length of the dry season) digging and maintaining their basins. For the basins+N scenario, this reduced to 29 and 48 minutes per day for the LRE and HRE household, respectively, given that fewer basins were required (Table 3.10).

Table 3.10 Time spent digging and maintaining basins under the basin scenarios.

	LRE Household		HRE Household	
	Basins	Basins+N	Basins	Basins+N
Number of basins required for 30% increase in total grain production	475	235	672	384
Time spent digging throughout dry season (minutes/household/day)	59	29	84	48
Total time spent digging each year (person-days/year)	14.9	7.4	21	12

Despite weeding under planting basins taking less time than farmers usual practices, farm labour use increased under both basin scenarios compared to baseline (Figure 3.13). For instance, the basin-only scenario increased mean annual person-days required by 9 and 16 days for the LRE and HRE household, respectively. The baseline+N scenario was shown to reduce farm labour demand compared to baseline. However, this is because of the higher rate of yield failure under this scenario, and thus no weeding being required in some seasons, rather than any productive labour savings.

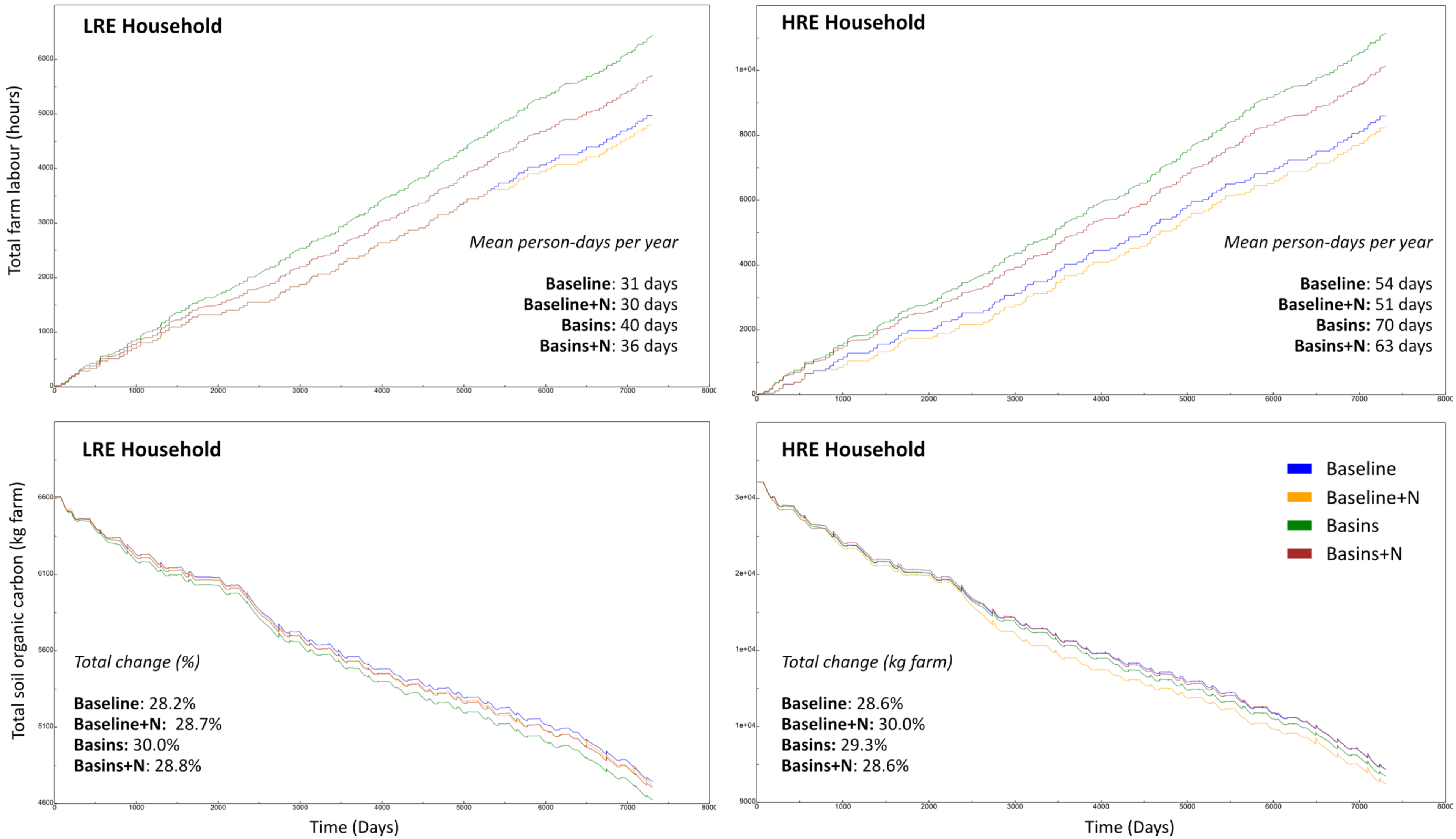


Figure 3.13 Total farm labour used (top panels) and total farm soil organic carbon (bottom panels) over the 20-year simulation run for each scenario. Text provides average annual values for each scenario.

3.5 Sustainability

For all four scenarios we saw a gradual decline in soil organic carbon (SOC) and nitrogen (SON) stocks over the 20-year simulation run (Table 3.11), suggesting none of the farm configurations are sustainable in the long-term unless combined with additional practices to replenish stocks (e.g., adding additional farmyard manure, retaining crop residue, using leguminous cover crops and green manures). The annual rates of SOC and SON depletion were similar across scenarios but slightly higher for the intervention scenarios, likely reflecting the greater crop growth and subsequent uptake of soil nutrients under these scenarios.

Another potential indicator of sustainability is the ratio between the amount of nitrogen applied (through manure and inorganic fertilizer) and the nitrogen contained within above-ground maize biomass. This ratio provides an indication of whether nitrogen is being utilised by the crop or leached from the soil (i.e., a ratio greater than 1 indicates potential nitrogen leaching, while a ratio less than 1 indicates the crop has taken up more nitrogen than was applied). Results from our scenarios suggest that using basins may reduce the amount of nitrogen leached when additional nitrogen fertilizer is applied (Table 3.11). This is also reflected in the lower surface-water run-off seen for the basin scenarios compared to non-basin scenarios (Figure 3.15).

Table 3.11 Soil indicators of sustainability by household and scenario.

	Scenario			
	Baseline	**Baseline+N**	**Basins**	**Basins+N**
Lower resource endowed household				
Nitrogen balance (N applied/ N in produce)	---	2.60 (0.45, 5.57)	---	0.22 (0.10, 1.20)
Annual change in SOC (%)	-1.4 (-3.1, -0.9)	-1.5 (-3.1, -0.9)	-1.5 (-3.2, -0.9)	-1.4 (-3.2, -0.9)
Annual change in SON (%)	-1.3 (-3.0, -0.9)	-1.3 (-2.9, -0.8)	-1.4 (-3.1, -0.9)	-1.3 (-3.0, -0.8)
Higher resource endowed household				
Nitrogen balance (N applied/ N in produce)	0.80 (0.20, 2.10)	2.10 (0.31, 3.85)	0.68 (0.21, 2.84)	0.81 (0.26, 3.89)
Annual change in SOC (%)	-1.4 (-2.5, -0.8)	-1.6 (-3.1, -0.8)	-1.5 (-2.7, -0.8)	-1.5 (-2.7, -0.8)
Annual change in SON (%)	-1.4 (-2.3, -0.8)	-1.4 (-2.9, -0.8)	-1.4 (-2.5, -0.8)	-1.4 (-2.4, -0.8)

Statistics presented: Median (Range)

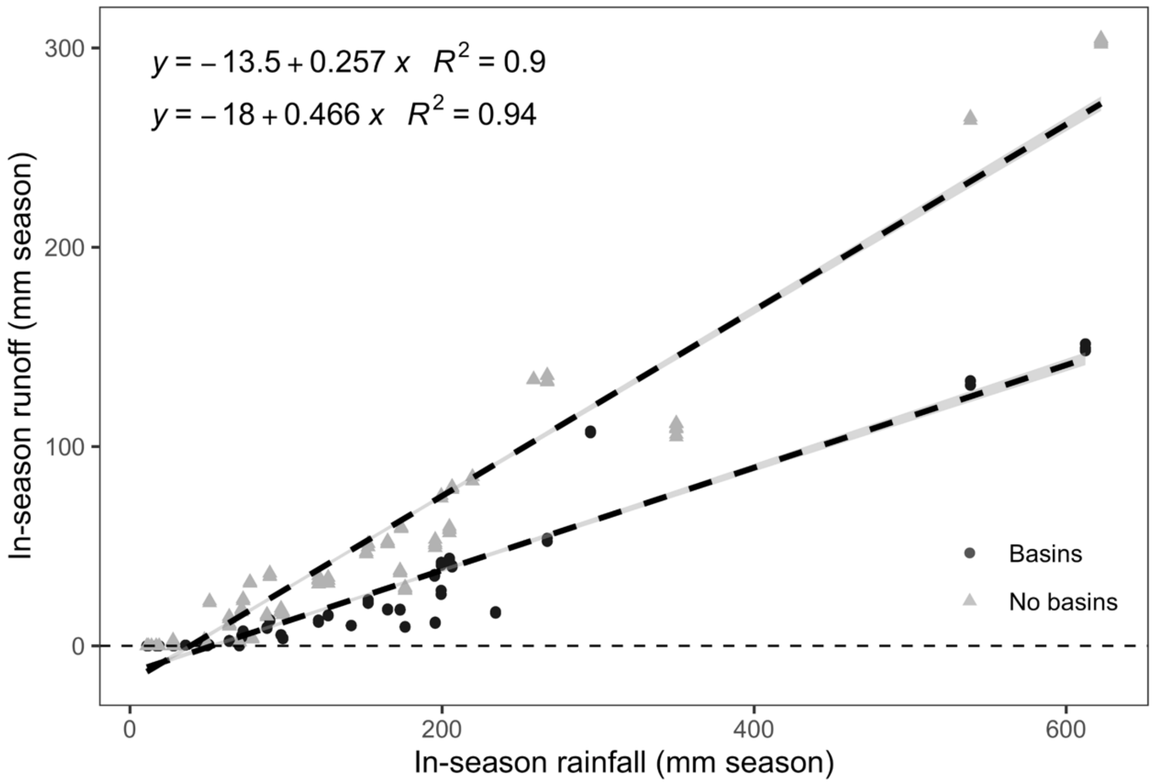


Figure 3.14 In-season run-off for both basin (i.e., basins-only and basins+N) and non-basin (i.e., baseline and baseline+N) scenarios regressed against in-season rainfall. Basin scenarios resulted in less surface water run-off than non-basin scenarios.

4. Discussion

4.1 Implications of the scenarios

Our model results suggest that, at least in the eastern drylands of Kenya, using planting basins for maize production can provide substantial benefits to smallholder farm households. Although unlikely to lead to transformational change in terms of income per capita, integrating basins into current farming systems could reduce variation in maize production, buffering against climate variability and providing a critical safety net in terms of household food security during times of drought. In line with empirical studies (Fatondji et al., 2007; Rockström et al., 2002), basin scenarios increased resource use efficiencies, providing more crop per drop of rainfall, hour of labour and kilogram of fertilizer. In contrast, scenarios where N fertilizer was applied without the use of basins increased yield variability, providing substantial yield gains in some years and large losses in others. N fertilizer-only scenarios did not reduce the risk of crop failures and resulted in less efficient use of water, labour, and nitrogen. In resource-constrained environments such as the drylands, increased production resilience and reduced risk are likely to be highly valued by smallholder farmers, especially those suffering from high levels of food insecurity. For many farmers in Makueni County, using planting basins with or without the use of N fertilizers is thus likely to be a more attractive option than the use of N fertilizer alone.

Our findings highlight the relevance of undertaking farm level assessments and the importance of not only considering variation in intervention performance between differing farming contexts (Coe et al., 2016; Vanlauwe et al., 2019), but also variation in performance under varying rainfall conditions. Using the model to extend the results from on-farm trials allowed us to assess the implications of using planting basins beyond just a few seasons and under variable rainfall conditions. Such evaluations are increasingly pertinent in the face of climate change, with increased rainfall variability and extreme weather events predicted for East Africa and Kenya (Rowell et al., 2015; Wainwright et al., 2021). Although we utilised past weather data, our model could equally be used with projected climatic data to understand and explore the potential impact of planting basins under future climate change scenarios.

The inter-annual variability in scenario performance demonstrated by our model also has implications for the trial and uptake of innovations by farming households and illustrates the importance of when and under what conditions technologies are tested. For instance, should a farmer have tested the planting basins in a year with exceptionally good rainfall, their basins may have provided only marginal gains relative to their usual practice. Subsequently, they may have been less likely to continue using basins despite the potential benefit to using basins under poorer rainfall conditions. One application of our model could thus be to demonstrate to farmers the potential temporal variation in basin performance and encourage farmers to test basins beyond a single growing season or illustrate that maintaining even a small area of basins in case of poor rains could be beneficial.

Such results also suggest an opportunity to complement technological innovations such as planting basins with interventions aimed at improving the enabling environment for their uptake, such as timely and accurate weather forecasts. Should farmers have access to locally relevant and accurate information they could tailor their farming practices to predicted rainfall conditions and decide how much to invest in certain options or combinations thereof. For instance, investing in the maintenance and construction of planting basins when poorer rainfall conditions are expected, and investing in the use of N fertilizer in those where more favourable rains are anticipated.

In addition to rainfall variability, declining soil fertility presents a pervasive challenge to increasing agricultural production in the drylands of Kenya, with many soils critically low in organic matter (Muoni et al., 2020; Okoba and Sterk, 2010). Several studies indicate that using planting basins can significantly improve a range of soil quality indicators including soil organic carbon (SOC) (Marumbi et al., 2020; Nyamangara et al., 2014). Increases in SOC under basins are attributed to the application of organic matter through use of manure; enhanced crop growth and root biomass and subsequent root decomposition; and reduced soil disturbances protecting soil carbon from microbial attack. It is therefore expected that continued use of planting basins will lead to a gradual build-up of SOC stocks (Marumbi et al., 2020). Yet our model results indicate that although basins reduced surface run-off and N leaching, total SOC stocks showed a steady decline under all scenarios including those where basins were used in combination with farmyard manure (i.e., the HRE household). This suggests that in addition to basins other improved practices may be needed to maintain SOC stores and soil fertility in the long-term (i.e., increased quantities of farmyard manure, retention of crop residues or use of mulch, compost, or green manures) or, alternatively, that our current APSIM model fails to capture the full benefit of basins and manure application and thus requires improvement.

In our application of the model, the lead-in time required for households to establish their basins was not considered. Households were assumed to already have the number of basins needed to increase total grain production by 30% at the start of the simulation run, with labour only being used to repair and maintain these basins during the dry season. In reality, farmers are likely to dig their basins incrementally over several seasons or years. If we assume the LRE and HRE households are willing to devote the same amount of time per day establishing their basins as they are maintaining their basins (i.e., 29 to 84 minutes per day during the dry season), it would take roughly 10 years for a household to dig the number of basins required in our scenarios. This implies that digging a sufficient number of basins to achieve transformational changes in maize self-provision (i.e., a 30% increase in total grain production) would require either a substantial initial investment from households (i.e., devoting long hours initially to establish basins or hiring external labour) or long lead-in times. In contrast, alternative options such as supplementary irrigation combined with N fertilizer could be implemented and would be effective immediately (assuming other barriers such as availability and access to such inputs can be overcome). Given that labour constraints are one, if not the primary barrier to using basins (Schuler et al., 2016, see also Chapter 4), a household's willingness to devote labour and resources to digging basins is an important area of further investigation, along with finding ways to mechanise basin excavation and reduce establishment costs.

The high labour demands associated with establishing and maintaining basins also raise the question of whose labour will be used. Several studies have reported a shift in labour burden from men to women with the uptake of basins, with women becoming more involved in land preparation (Crossland et al., 2021; Nyanga et al., 2012, see also Chapter 4). While our model accounts for gender of household members in terms of daily grain demand, family labour is pooled, and men's and women's labour are not differentiated. In reality, individuals within the same households are likely to have different roles and responsibilities and contribute to a household's livelihood strategy in distinct ways (Crossland et al., 2021a, 2021b, see also Chapter 4 and 5). Nevertheless, farm household models rarely integrate gender and social inclusion considerations (Micheletti and Elias, 2019). A priority area for future development of our model is thus the explicit consideration of gender-differentiation within the household, such as in the gender divisions of labour and distribution of costs and benefits from innovations.

Against the backdrop of often complex trade-offs between different livelihood activities, returns to labour are likely to be a key consideration for smallholder farm households, especially those with alternative livelihood options. In our study area, it is common for adult men to seek off-farm employment in cities and nearby towns (Crossland et al., 2021a, 2021b, see also Chapter 4 and 5; Ifejika Speranza, 2006). Planting basins thus not only need to be attractive compared to existing and alternative farming options, but also in comparison to off-farm opportunities. Although we did not explore off-farm income opportunities explicitly through our model scenarios, comparing average returns to labour from maize production under planting basin scenarios with average wage rates from off-farm income sources, provided several insights.

Despite basins requiring more labour per hectare than farmers usual tillage practices, only basin scenarios provided average returns similar to those of working as a local agricultural labourer. Nevertheless, we saw large variation in scenario performance. In some years, all scenarios provided returns greater than the average wage for a highly skilled labour in Nairobi, while in other years they failed to provide a positive return at all. These results highlight the risk of rain-fed agriculture but also suggest that investing in maize production may still be worthwhile for at least some household members in some years, especially if non-farm income opportunities are limited and unreliable.

4.2 The value and limitations of the modelling approach

A novel aspect of our modelling approach was the integration of an APSIM crop model and a farm-scale Simile model. Our study provides a first use case for integrated APSIM-Simile models and demonstrates their potential utility in evaluating the impact, tradeoffs, and viability of agricultural innovations at both the plot and farm scale. For example, using our model to assess what would be needed to lift grain production by a given threshold (i.e., 30%) using different interventions, demonstrates how such APSIM-Simile farm-scale models could be used to provide context-sensitive recommendations or input for farmer-led participatory trials. For instance, the model could be used with farmers to develop various option scenarios and to aid discussion and decisions over which options they would like to trial on their farms (Vanclay et al., 2006). Parameterising our model for two households with contrasting resource endowment also illustrates its flexibility and the ability to create system- or site-specific variations. As it stands, our model provides a useful proof of concept for future APSIM-Simile livelihood models and underscores the need to evaluate agricultural innovations in a much broader sense than currently done within agricultural research and development. However, several areas require improvement and further development.

Although large models with multiple components that try to capture all possible processes and levels of integration are unlikely to be useful or desirable (Silva and Giller, 2021), our model lacks detail in several of its submodels and their interactions. For instance, in our application of the model, we only considered the production of maize, yet households in eastern Kenya typically grow a variety of crops and maize is often intercropped with various legumes such as pigeon pea (*Cajanus cajan*) and cowpea (*Vigna ungulata*). Furthermore, while water and nitrogen limitation of maize production are well considered in our model, growth-reducing factors such as weeds, pests and disease are not, despite being a major challenge in closing yield gaps in smallholder farming systems (Donatelli et al., 2017; Silva and Giller, 2021). Our model therefore likely overestimates maize production and households' self-provision. Similarly, our livestock model is limited in its representation of heard dynamics and overlooks the influence of increased maize stover production on meat and milk production, and livestock sales.

Many of these limitations could be overcome through further model development and APSIM-Simile integration. For instance, APSIM offers a vast library of crop models and cultivar options, including cowpea and pigeon pea, and has the capability to model intercropping systems (Malézieux et al., 2009), weeds, and even tree-crop interactions (Dilla et al., 2020; Smethurst et al., 2017). Future model development could therefore allow for more realistic and complex cropping systems to be explored.

Given our model's current assumptions and simplifications, caution is needed when basing management decisions on its outputs. To be useful, models and their outputs must be credible, and their underlying uncertainty and validity explored. While the sensibility and robustness of model and submodel outputs were considered throughout development, further testing and validation of our model will be needed to ensure confidence in its ability to adequately represent a range of livelihood systems and produce realistic outputs.

This includes collecting experimental data on the function of basins under a range of conditions and performing traditional validation tests (i.e., comparing simulated and observed data) or sensitivity analysis to further explore model performance and behaviour under a range of agronomic scenarios (Holzworth et al., 2011).

By conducting iterative runs of a model and systematically changing parameters and initial values, sensitivity analysis can be used to determine the sensitivity of the model and its outputs to different choices in parameter values and initial conditions (Dent and Blackie, 1979). Such analyses can help identify parameters and elements that result in significant changes in model output and for which greater examination may be required, especially when our knowledge of such areas is limited. Subsequently, sensitivity analysis can result in changes and improvements to model structure and inform research priorities to help fill critical knowledge gaps and improve our understanding of a system's behaviour and response to change.

In this study, we have not explicitly explored or quantified the uncertainty of model outputs and parameter sensitivity. Sensitivity analysis becomes increasingly complex and arduous with large models like ours, which have numerous interactions between parameters and many input and output variables of interest. Conducting a robust analysis would likely require the use of Monte Carlo techniques where all parameters and initial values of interest are varied simultaneously in a vast number of combinations and the ability to run hundreds and even thousands of simulations to fully explore the collective sensitivity of parameter combinations

(Hannon and Ruth, 1997). While beyond the scope of the present study, such analysis would substantially improve the usefulness of our model and is an essential next step.

Nevertheless, although not a substitute for sensitivity analysis and systematic exploration of uncertainty, applying a model can be seen as an initial step of such enquiry (Dent and Blackie, 1979; Hannon and Ruth, 1997). For instance, running our model over again and evaluating the plausibility of its results throughout the development process and using the model to explore different scenarios provided a feel for which parameters and elements of our model may be sensitive and warrant further exploration through such sensitivity analysis. Such aspects include the availability of on-farm labour and off-farm employment and the time required to dig and maintain planting basins. These variables are likely to influence planting date, which has a significant effect on final yields under rain-fed conditions. Development of our model was also largely informed by secondary data collated and synthesised by researchers with limited input from farmers. Taking a more participatory, co-learning approach to model development and evaluation, is thus likely to further advance the saliency and legitimacy of our model (Lynam, 2016; Vanclay et al., 2006).

Simile has been used in participatory modelling approaches with rural communities in Indonesia (Purnomo et al., 2003), Zimbabwe (Prabhu et al., 2003; Standa-Gunda et al., 2003) and Cameroon (Legg, 2003). Through structured stakeholder engagements between local people, researchers, and modellers, these studies developed simulation models to explore natural resource management scenarios identified by local communities. During workshops, participants designed conceptual hand-drawn models (e.g., on a whiteboard) that were then translated into the Simile modelling environment with technical assistance from modellers. Participants then discussed and debated the relationships between the different components of the model, ran scenarios and assessed the plausibility of model outputs. In the case of our model, a similar approach could have been used to develop the model in collaboration with groups of farmers. Although this would have likely resulted in a different model structure, the involvement of local actors is likely to improve their confidence in a model and its outputs and ensure that models address local needs and interests (Vanclay et al., 2006).

Simile provides an excellent tool for participatory modelling since it has several functionalities that help facilitate collaborative model development:

- Simile is an icon-based modelling environment with an intuitive user interface and does not require extensive programming knowledge. This allows rapid model construction and model structure to be easily communicated (Figure 3.15).
- Simile includes a sketch graph tool that allows users to draw the relationships between two variables by hand. This is particularly useful when developing models in data-sparse environments and incorporating expert knowledge (Figure 3.15).
- Simile offers a suite of customisable output display tools that allow users to visualise model outputs as the model runs and can help communicate model results to a wide range of audiences (see Figure 3.15).
- Simile models are often fast to run, allowing for rapid model development. For example, the model presented in the present study takes between 58 to 97 seconds to run a 20-year simulation[15], depending on the type and number of visual displays selected.

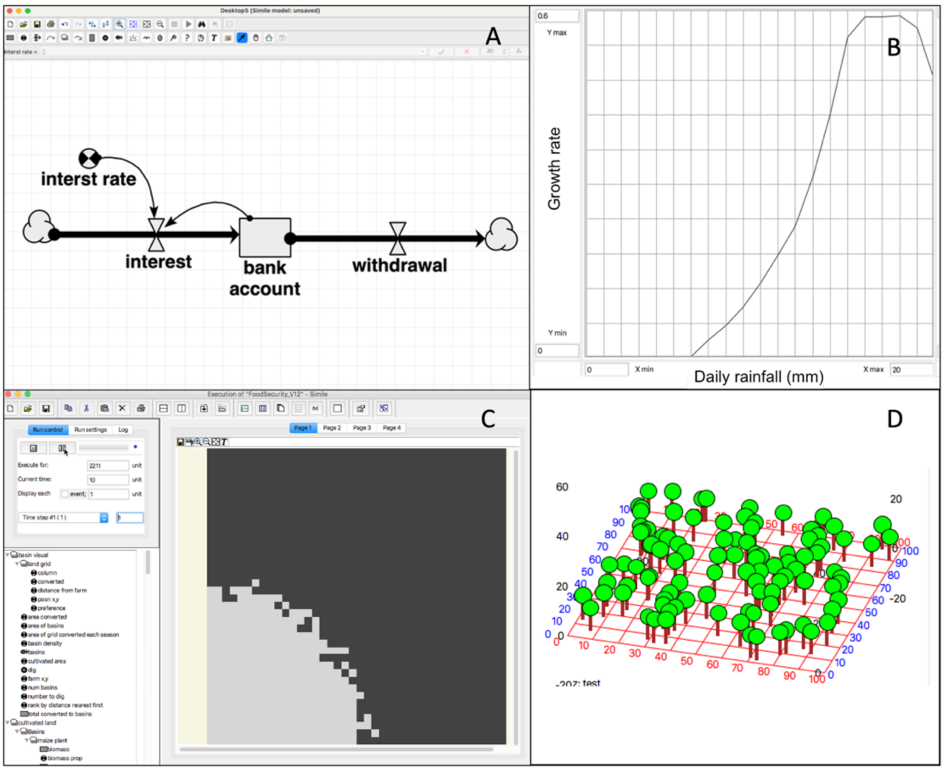


Figure 3.15. Example of Simile's user interface and output display tools. A) a simple model of a bank account illustrating Simile's icon-based user interface; B) the relationship between two variables (growth rate and rainfall) hand-drawn using Simile's sketch graph tool; C) one of

[15] When run on an Asus Vivo Notebook (2018), Intel Core i3-7100u 24 GHz, 4 GB LPDDR3, 128 GB Mz SATA3 SSD.

Simile's display tools showing changes in farm area under basins (light grey pixels) over time; and D) another display tool depicting the location and size of on-farm trees.

5. Conclusion

For agricultural innovations to be widely adopted they not only need to be productive and profitable they also need to be attractive within the broader context of smallholder livelihood systems. Despite reports of impressive yields from planting basins, few studies have assessed the extent to which basins can contribute to transformational change in household food security and livelihood outcomes. In this study, we presented a farm-scale model that extends results from participatory on-farm trials to explore variability in basin performance at both the field and farm scale. Our model results underscore the need to evaluate innovations in a much broader sense than usually done and suggest that, although unlikely to lead to transformational change in terms of household income, integrating basins into current farming systems could provide a critical safety net in terms of household food security in the face of increasing climate variability. Finally, taking a novel approach in the dynamic integration of two modelling environments, our model provides one of the first examples of APSIM-Simile integration and demonstrates the potential utility of APSIM-Simile models in evaluating the impacts and viability of agricultural innovations and providing context-sensitive recommendations.

Chapter 4: Understanding How Intrahousehold Gender Dynamics Shape the Scaling-up of Land Restoration

The following chapter has been published as: Crossland et al. "On the Farm, into the Home: How Intrahousehold Gender Dynamics Shape Land Restoration in Eastern Kenya." Ecological Restoration vol. 39 no. 1-2: 90-107.

Results from this chapter were also presented at the 'Seeds of Change: Gender Equality through Agricultural research for development' conference, University of Canberra, Australia (April 2019) and the CGIAR Research Program on Forest, Trees and Agroforestry Science Conference (March 2021).

1. Introduction

Land restoration and avoiding further degradation is seen as a critical pathway to achieving multiple global objectives, from improving food security and ending poverty, to mitigating climate change and conserving biodiversity (Cowie et al., 2018; IPBES 2018). As a result, the past decade has seen an unprecedented commitment to restoring deforested and degraded land. Under initiatives such as the Bonn Challenge and the UN Sustainable Development Goals, governments across the globe have pledged to restore hundreds of millions of hectares of degraded land by 2030, while the UN recently declared 2021-2030 the "Decade on Ecosystem Restoration". More than two billion hectares of land are estimated to offer opportunities for restoration worldwide, and a large proportion are located in sub-Saharan Africa (SSA), on or adjacent to agricultural lands (Minnemeyer et al., 2011). Meeting national restoration commitments therefore depends on the cumulative effect of management decisions made by smallholder farmers to adopt restorative farming practices – defined here as farming activities that aim to avoid, reduce, or reverse degradation processes and increase ecosystem service provision.

In the eastern drylands of Kenya, a major driver of land degradation is the use of unsustainable agricultural practices (Tiffen et al., 1994). For example, practices that do not replenish soil nutrients and that lead to soil erosion, including inappropriate land preparation, removal of crop residues and limited use of organic inputs such as farmyard manure. As a result, cultivated lands are often characterised by nutrient-depleted, crusted soils, low in organic carbon and prone to erosion and compaction (Gitau et al., 2006; Rockström et al., 2009).

Increasing tree cover on farms is often considered a key approach to dryland restoration. This is due to the multiple ecological and socio-economic benefits trees provide including enhanced soil fertility, erosion control, improved water cycling, carbon sequestration and the provision of tree products such as timber, medicine and food (Brancalion et al., 2019; Lohbeck et al., 2020). Consequently, Kenya has set a target of maintaining over 10% tree cover by 2022, including on agricultural lands (MEF 2019). Another promising dryland restoration practice is the use of planting basins, a soil and water conservation technique where small pits are dug, usually in a grid formation, filled with farmyard manure and crops planted within them. These basins reduce surface run-off and soil erosion, increase infiltration through breaking through soil crusts and hardpans, and improve soil fertility and water availability, helping to bridge intra-seasonal dry spells and increase crop yields under arid conditions (Mazvimavi and Twomlow, 2009; Muli et al., 2017).

While promising restorative farming practices such as tree planting and planting basins exist for drylands, reaching large numbers of farmers and changing current farming practices will require an understanding of which restoration options best suit different farming and farmer circumstances and the potential barriers to their adoption (Sinclair and Coe, 2019). On-farm restoration practices such as tree planting and planting basins are also likely to have strong gender-dimensions to their uptake and use. Common barriers to the adoption of agricultural innovations by smallholder farmers, and in particular women, include a lack of access to resources such as land, water and labour; capital and credit constraints; inadequate extension services, and limited market access (Magruder, 2018; Meinzen-Dick et al., 2012; Ragasa et al., 2014). While most adoption studies consider the influence of these impediments at the household level and the disparities between male- and female-headed households, less attention has been paid to the role of intrahousehold dynamics – the relations between men and women within the same household that influence the division of labour and the use, control and ownership of household resources (Doss, 2013; Doss and Morris, 2001; Haider et al., 2018).

Many adoption studies still frame technological change in terms of the economic rationality of individual choices, but there is growing recognition that innovation (the widespread adoption of change) is shaped by social relations and negotiations amongst actors, including those living within the same household (Badstue et al., 2020; Farnworth et al., 2020; Glover et al., 2019). In households with multiple decision-makers, changes made to farming activities and practices (innovations), are often negotiated between multiple members, each with differing preferences, priorities and bargaining power (Shibata et al., 2020; Theis et al., 2018). Even when men and women within the same household manage separate plots of land, decisions over the allocation of household labour and resources may be negotiated at the household level (Doss and Meinzen-Dick, 2015; Doss and Quisumbing, 2020). Restoration initiatives that target farmers without considering their whole household and all of those involved in decisions over the use of an innovation (uptake decisions) may be less effective than those that do.

Intrahousehold bargaining power is strongly associated with ownership and control of assets and resources, such as land (Deere and Doss, 2006; Meinzen-Dick et al., 2011). In Kenya, despite the national constitution granting men and women equal rights to inherit and own land, women's land rights remain restricted by customary norms, with women typically attaining secondary use rights through their husbands rather than inheritance (Musangi, 2017). As a result, men typically exercise greater control over decisions regarding agricultural activities, particularly those involving more permanent, long-term investments such as tree planting (Kiptot and Franzel, 2012).

In addition to considering who is involved in uptake decisions over restorative farming practices, it will also be essential to consider whose labour will be used or saved by their adoption. Changes in farming practice can alter the amount of labour required and the timing of associated activities and who is responsible for these tasks (Njuki et al., 2014; Theis et al., 2018). Rural women are often primarily responsible for much of the work within the home; innovations that require additional labour thus risk increasing their already heavy workloads (Doss, 2001; Njuki et al., 2016). Since on-farm restoration practices are typically labour-intensive (e.g., planting trees, constructing soil and water conservation structures, fencing exclosures), the extent to which associated labour changes benefit or disadvantage men and women requires careful consideration. For example, in Southern Africa, the uptake of planting basins has been reported to shift the burden of land preparation from men to women (Baudron et al., 2007; Nyanga et al., 2012).

In this paper, we contribute to both the literature on restoration practice and agricultural technology adoption more broadly, by shifting the restoration focus onto the farm and considering the role of intrahousehold dynamics in the initial uptake and adaptation of two on-farm restoration practices: tree planting and planting basins; with over 2,500 farmers in eastern Kenya. Specifically, we ask: how do intrahousehold decision-making dynamics and gender relations influence the uptake of restorative farming practices? And, in turn, how do these restorative practices and how they are disseminated, influence gender relations and divisions of labour within the household? Through answering these questions, we identify key entry points for improving the dissemination of on-farm restoration practices in the eastern drylands of Kenya and offer recommendations for achieving more inclusive and gender-equitable restoration outcomes.

2. Methods

This research was embedded in a dryland restoration project working with over 2,500 smallholder farmers in eastern Kenya (World Agroforestry, 2020). The project sought to improve the livelihoods and food security of smallholder farm households through supporting local innovation and encouraging farmers to systematically test and adapt restoration practices that they were interested in (Coe et al., 2014). This involved planned comparisons (PCs), where farmers choose and compare the performance of different options and corresponding variations thereof, in their own terms, on their own farms (Coe et al., 2017). Researchers and development partners then work with farmers to monitor the performance of each option across a range of social and ecological contexts to develop an evidence base for identifying which options work best where and for whom (Sinclair and Coe, 2019).

Over a five-year period, the project worked with farmers to conduct PCs involving two restorative farming practices: tree planting and planting basins. A significant barrier to increasing tree cover, particularly in the drylands, is low seedling survival caused by erratic climate, inappropriate management practices and use of ecologically unsuitable species (De Leeuw et al., 2014; Derero et al., 2020; Ndegwa et al., 2017). The project thus worked with farmers to compare the effect of different planting and management practices on tree seedling survival, including planting hole size, planting with/without manure and different watering regimes (Magaju et al., 2020). Seven drought-tolerant, multipurpose tree species, many of which provide both ecological and socio-economic benefits, were selected through consultative workshops with farmers (Table 4.1).

The second planned comparison involved planting basins. While basins have long been promoted in arid areas of SSA, including Kenya, questions remain regarding the most appropriate size of basin and soil treatment for different farming contexts (Danjuma and Mohammed, 2015). Farmers, therefore, compared *Zea mays* (maize) yield in different basin sizes and manure treatments against their usual cultivation practices of ox plough or hand hoe cultivation. This study focused on the intrahousehold dynamics and gender relations associated with farmers' involvement in these PCs and their implementation of the practices.

Table 4.1 Tree species distributed by the project (Magaju et al., 2020), their uses and environmental and socio-economic benefits *(Orwa et al., 2009)*.

Tree species	Uses and benefits (Orwa et al., 2009)	Total seedlings planted (Magaju et al., 2019)
Mangifera indica (mango)	Fruit, apiculture, timber, firewood, charcoal, shade/shelter, tannin/dyes, medicine, soil improvement: mulch	15,226
Melia volkensii (melia)	Timber, apiculture, livestock fodder, pesticide	7,330
Azadirachta indica (neem)	Erosion control, medicine, pesticide, timber, fruits, charcoal, shade/shelter, tannin/dyes.	5,618
Senna siamea (Siamese senna)	Livestock fodder, erosion control, firewood, charcoal, timber, soil improvement: mulch, medicine, shade/shelter, tannin/dyes	3,905
Moringa oleifera (moringa)	Vegetable/oil, erosion control, livestock fodder, apiculture, fibre, tannin/dyes, medicine, soil improvement: mulch	1,702
Carica papaya (pawpaw)	Fruit, medicine	1,068
Calliandra calothyrsus (Calliandra)	Livestock fodder, erosion control, apiculture, firewood, fibre, shade/shelter, soil improvement: nitrogen fixing and mulch	348

2.1 Study sites

The study was conducted across six sub-counties in Machakos, Makueni and Kitui counties in eastern Kenya (Figure 2.2, Chapter 2). This semi-arid region is characterised by small-scale, rain-fed agriculture subject to frequent drought and crop failures caused by increasingly unreliable rainfall (KNBS 2019). Agricultural productivity is limited by extensive land degradation and many rural households experience food insecurity (KFSSG, 2019). The sites were selected to cover a range of socio-ecological conditions and vary in average annual precipitation and temperature (Table 2.2, Chapter 2) and their proximity to urban centres (Figure 2.2, Chapter 2), influencing their connectivity to markets, off-farm employment opportunities and agricultural potential.

2.2 Data Collection and Analysis

In 2018, structured surveys were conducted with 1,293 and 511 farmers across the six sites to monitor the tree planting and basin PCs, respectively (Table 4.2). These surveys included questions detailing who was involved with decision-making and implementation. A household survey was also used to collect basic socioeconomic data on each farmer and their household (Winowiecki et al., 2019). All surveys were administered using Open Data Kit Collect installed on smart-phones (Hartung et al., 2010) and by trained enumerators who spoke the local language (Kamba). Descriptive analysis of survey data was conducted in the R software environment (R Core Team, 2020).

Interviews with 62 farmers and 12 sex-segregated focus group discussions (FGDs) were then conducted to explore patterns arising from the surveys (Table 4.2). Key areas of enquiry included: how decisions over the PCs and agricultural innovations, in general, are made; women's agency – specifically, their ability to influence uptake decisions (Kabeer, 1999); gender-related roles and norms surrounding farming activities and divisions of labour within the household; and the benefits and challenges associated with tree planting and basins.

FGDs included the use of vignettes (short stories) to explore community-level trends in decision-making. This involved reading participants vignettes depicting different levels of consultation over the uptake of agricultural innovations. These vignettes were developed to cover a range of decision-making dynamics and included the various types of consultation identified from interviews. Each participant was asked to vote, in private, on which male and female vignette best described how men and women within their community typically make uptake decisions. Voting results then formed the basis for further discussion around men's and women's involvement in uptake decisions, including participants' reasons for choosing a particular vignette and their perceptions on spousal disagreement and negotiation regarding uptake decisions.

For the interviews and FGDs, stratified random sampling was used to ensure the representation of men and women involved in the two PCs. However, our resulting sample shows a bias towards women since men were often engaged in off-farm activities and thus unavailable to participate. For the interviews, questions were translated into Kamba and piloted with eight farmers. All interviews were audio-recorded and transcribed into English. Following data collection, qualitative analysis was performed using NVivo 11 software (QSR International, 2015). Textual data from interview transcripts and notes from FGDs were deductively coded for content analysis using a coding tree developed from the interview and FGD facilitation guides. Additional codes were later inductively developed based on dominant topics raised by participants.

Table 4.2 Gender of study participants involved in the surveys, interviews and focus group discussions in each site.

	Machakos		**Makueni**		**Kitui**		
	Mwala (n = 145)	**Yatta (n = 357)**	**Kibwezi East (n = 322)**	**Mbooni East (n = 189)**	**Mwingi East (n = 582)**	**Kitui Rural (n = 378)**	**Total (n = 1973)**
Planting basin survey							
Men	14	7	25	13	20	24	103
Women	26	34	65	62	73	148	408
Tree planting survey							
Men	33	53	34	44	203	62	429
Women	45	238	158	47	260	116	864
Individual interviews							
Men	2	4	4	3	3	3	19
Female	8	7	7	8	6	7	43
Focus group participants							
Men	5	6	7	5	9	9	41
Female	12	8	22	7	8	9	66

3. Results

3.1 Farmer and Household Characteristics

The majority of farmers involved in the PCs were married, aged between 36-55 and female (Table 4.3). However, a higher percentage of men were involved in the tree planting PC than the basin PC. We also saw several differences in farmer characteristics across sites. A higher percentage of participants in Mwala saw farming as their primary source of income, were more food secure and male. This likely reflects Mwala's better connection to urban markets and more favourable farming conditions, resulting in men being more interested in investing in agricultural innovations. Similarly, 49% of Makueni participants reported having a secondary source of income from off-farm activities, compared to only 35% and 22% in Kitui and Machakos counties, respectively. This likely reflects the high rates of male outmigration and off-farm employment found in Makueni County (Crossland et al., 2021). Households in Kitui were also less well-off than in Machakos and Makueni counties, in that they were more dependent on food aid, less connected and live in less permanent housing.

Table 4.3 Socio-economic characteristics of farmers participating in the planned comparisons. Statistics presented: count (%) and mean (SD).

	Tree planting planned comparison						
	Machakos County		**Makueni County**		**Kitui County**		
	Mwala (n = 78)	**Yatta (n = 291)**	**Kibwezi East (n = 192)**	**Mbooni East (n = 91)**	**Mwingi East (n = 463)**	**Kitui Rural (n = 178)**	**Total (n = 1293)**
Gender (women)	45 (58 %)	238 (82 %)	158 (82 %)	47 (52 %)	260 (56 %)	116 (65 %)	864 (67 %)
Married	66 (85 %)	234 (80 %)	172 (90 %)	67 (74 %)	411 (89 %)	160 (90 %)	1110 (86 %)
Age	48.9 (12.8)	49.5 (14.2)	43.6 (11.9)	46.2 (12.6)	44.9 (12.7)	44.9 (13.5)	46.0 (13.2)
Household size	4.7 (2.7)	5.3 (2.3)	5.4 (1.7)	6.6 (4.0)	6.2 (2.6)	6.1 (2.5)	5.8 (2.6)
Farm size (ha)	2.4 (1.4)	2.4 (11.8)	3.1 (3.7)	7.4 (11.3)	4.0 (2.3)	1.8 (1.2)	3.3 (6.8)
Primary source of income (farming)	73 (94 %)	201 (69 %)	158 (82 %)	71 (78 %)	371 (80 %)	163 (92 %)	1037 (80 %)
Secondary source of income (off-farm income)	11 (14 %)	74 (25 %)	99 (52 %)	41 (45 %)	116 (25 %)	89 (50 %)	430 (33 %)
Estimated distance to main road (km)	2.1 (2.2)	2.3 (2.4)	1.6 (1.7)	1.7 (1.4)	7.0 (5.0)	1.8 (1.4)	3.8 (4.2)
Received food aid in past five years	1 (1 %)	5 (2 %)	7 (4 %)	7 (8 %)	277 (60 %)	64 (37 %)	362 (30 %)
House with a permanent roof	72 (92 %)	247 (85 %)	160 (83 %)	86 (95 %)	237 (51 %)	109 (61 %)	911 (70 %)
	Planting basin planned comparison						
	Machakos County		**Makueni County**		**Kitui County**		
	Mwala (n = 40)	**Yatta (n = 41)**	**Kibwezi East (n = 90)**	**Mbooni East (n = 75)**	**Mwingi East (n = 93)**	**Kitui Rural (n = 172)**	**Total (n = 511)**
Gender (women)	26 (65 %)	34 (83 %)	65 (72 %)	62 (83 %)	73 (78 %)	148 (86 %)	408 (80 %)
Married	34 (85 %)	34 (83 %)	83 (92 %)	65 (87 %)	81 (87 %)	152 (88 %)	449 (88 %)
Age	51.6 (11.0)	55.3 (14.5)	47.1 (13.4)	45.5 (10.9)	42.9 (7.6)	45.6 (12.1)	46.6 (12.0)
Household size	4.0 (2.1)	6.3 (2.6)	5.5 (1.7)	6.7 (4.4)	6.6 (2.3)	6.2 (2.4)	6.0 (2.8)
Farm size (ha)	2.2 (2.4)	1.6 (1.1)	3.8 (5.4)	4.5 (5.3)	4.3 (2.3)	1.7 (1.1)	3.0 (3.6)
Primary source of income from farming	36 (90 %)	22 (54 %)	78 (87 %)	46 (61 %)	73 (78 %)	166 (97 %)	421 (82 %)
Secondary source of income (off-farm income)	7 (18 %)	7 (17 %)	43 (48 %)	35 (47 %)	28 (30 %)	87 (51 %)	207 (41 %)
Estimated distance to main road (km)	2.7 (3.7)	2.3 (2.3)	1.7 (1.3)	1.3 (0.9)	7.1 (4.9)	1.4 (1.1)	2.7 (3.3)
Received food aid in past five years	1 (3 %)	0 (0 %)	22 (24 %)	28 (37 %)	34 (37 %)	60 (35 %)	145 (28 %)
House with a permanent roof	39 (98 %)	32 (78 %)	74 (82 %)	71 (95 %)	58 (62 %)	113 (66 %)	387 (76 %)

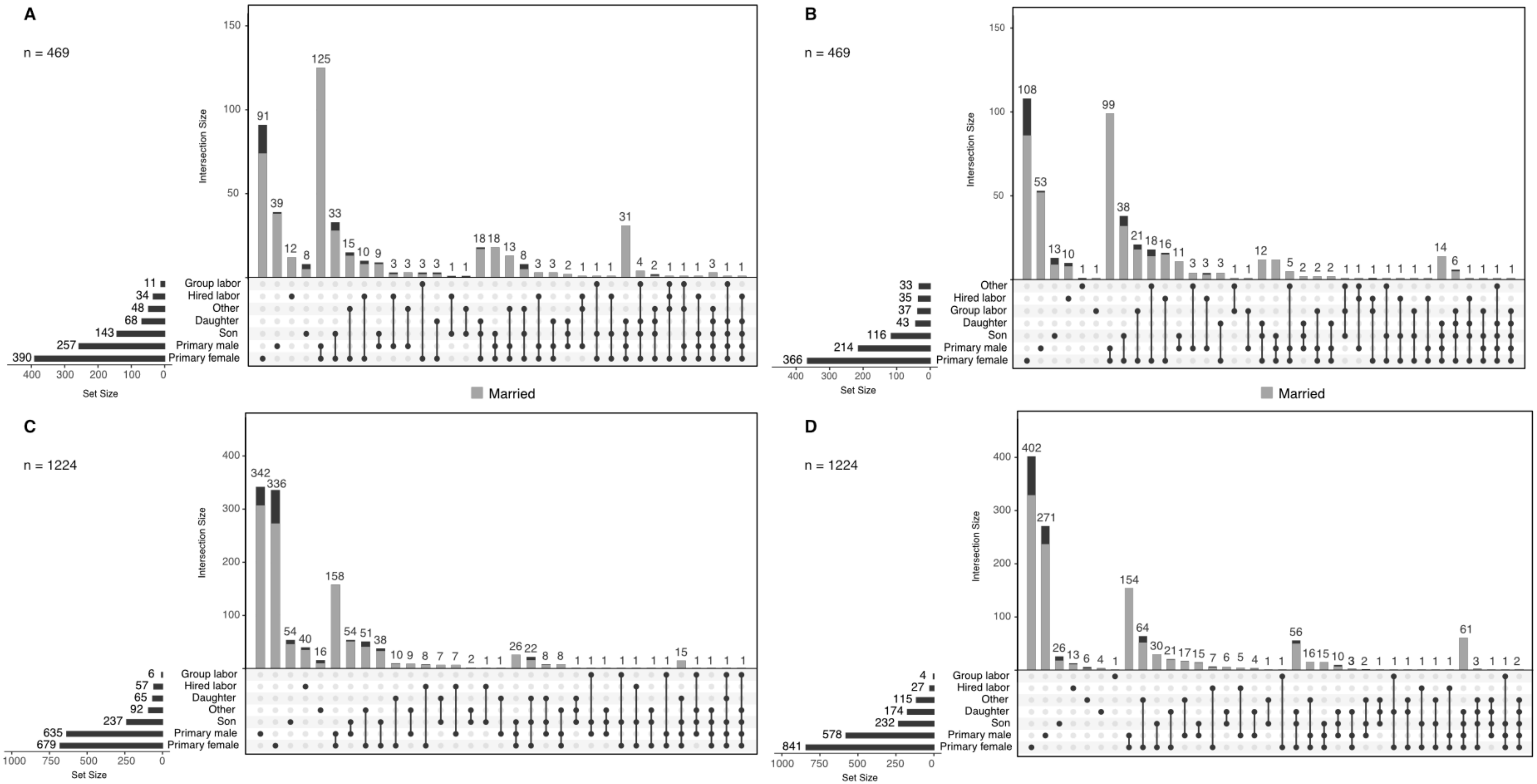
3.2 Household's Decision to Take Part in the Planned Comparisons

Our survey indicated that the household's decision to participate in the PCs was most often made by men and women respondents independently, although sometimes jointly with their spouse (Table 4.4) – a trend reflected in our interviews, with 63% and 69% of men and women having self-decided over the PCs, respectively. However, surveyed men's and women's involvement in this decision varied with restoration practice and respondent's gender and marital status, likely reflecting differences in labour requirement and the gender-related roles and norms surrounding tree tenure and outputs from innovations. For married respondents, more men than women reported that their spouse alone had decided to be involved in the basin PC, possibly reflecting that basins are mainly used to grow maize for household consumption – a predominantly female responsibility. For tree planting, there were fewer joint decisions and more men than women made the decision alone, likely reflecting local customary norms surrounding tree tenure, with tree planting and felling traditionally a male domain (Kiptot and Franzel, 2012). Greater joint decision-making over the basin PC compared to the tree planting PC could also reflect that, compared to tree planting, digging basins involved substantial labour contributions from other household members (Figure 4.1). Nevertheless, it should be noted that disparities in men's and women's answers may also be because men are systematically less likely than women to report women's involvement in farming decisions (Ambler et al., 2019; Anderson et al., 2017; Deere and Twyman, 2012). Unmarried respondents largely self-decided over the PCs, with no discernable differences with gender or practice.

Table 4.4 Those involved in the household's decision to participate in the planned comparisons. Statistics presented: count (%) and Fisher's exact test (two-sided). Unmarried includes single, divorced and widowed.

	Who decided to be involved in the planned comparison?				***p*-value**
	Myself	**Jointly**	**Spouse**	**Other**	
Planting basins					
Married women (n = 345)	209 (61 %)	125 (36 %)	2 (1 %)	9 (3 %)	< 0.001
Married men (n = 94)	54 (57 %)	30 (32 %)	8 (9 %)	2 (2 %)	
Unmarried women (n = 44)	43 (98 %)	0 (0 %)	0 (0 %)	1 (2 %)	---
Unmarried men (n = 3)	3 (100 %)	0 (0 %)	0 (0 %)	0 (0 %)	
Tree planting					
Married women (n = 758)	521 (69 %)	200 (26 %)	23 (3 %)	14 (2 %)	< 0.001
Married men (n = 382)	322 (84 %)	48 (13 %)	6 (2 %)	6 (2 %)	
Unmarried women (n = 106)	104 (98 %)	---	---	2 (2 %)	0.587
Unmarried men (n = 47)	45 (96 %)	---	---	2 (4 %)	
Married women					
Planting basins (n = 345)	209 (61 %)	125 (36 %)	2 (1 %)	9 (3 %)	< 0.001
Tree planting (n = 758)	521 (69 %)	200 (26 %)	23 (3 %)	14 (2 %)	
Married men					
Planting basins (n = 94)	54 (57 %)	30 (32 %)	8 (9 %)	2 (2 %)	< 0.001
Tree planting (n = 382)	322 (84 %)	48 (13 %)	6 (2 %)	6 (2 %)	

Figure 4.1 Upset plots of who was involved in A) digging the planned comparison planting basins, B) preparing land using farmers usual cultivation practice; C) planting the planned comparison tree seedlings, and D) watering the planned comparison tree seedlings. Upset plots employ a matrix-based layout to show intersections of sets and their frequencies (e.g., data from a multiple response question) (Conway et al., 2017). The bottom left bar chart shows the total number of respondents that selected each answer (set), the dot plot displays the various answer combinations (intersections), and the upper bar chart shows the number of respondents who answered using each combination (intersection size).



3.3 Intrahousehold Decision-Making Dynamics

Although our survey suggested that uptake decisions were largely made individually, our FGDs revealed a more complex story and that, although initiated by individuals who attend agricultural workshops, acting on this decision often still involved some form of consultation between husband and wife. During the vignette exercise, over three-quarters of FGD participants indicated stories depicting some form of consultation as best-representing how men and women in their community take decisions (Table 4.5).

Asked why spouses usually consult over uptake decisions, both men and women explained that consultation helps avoid conflict within the household and that those who do not consult may miss out on valuable farming advice. Consultation was also used, particularly by men, to ensure household members felt included in a decision and would thus support an activity by providing their labour. For example, wives excluded from decisions over tree planting might be less likely to "*protect the trees*" or "*help manage them*". Similarly, women reported that if a man fails to consult their wife, "*the project will not go forward because women are the tree caretakers*", or that she may challenge his decision: "*[the husband] doesn't want there to be conflict, so he consults his wife, otherwise she would ask "why did you buy this species?!".*

Unlike the vignettes representing women, FGDs were more divided over which of the vignettes depicting men were most representative. Although most men and women voted for the male vignette with the highest level of consultation, a substantial number voted for the vignette where the man alone decides to buy the trees but consults his wife on where to plant them. Some men explained that they prefer not to tell their wives that they are buying tree seedlings so their wives cannot disagree. One man asserted, "*if the man asks whether to spend money on trees [his wife] would disagree with buying them and want to spend the money on other things. But if you go buy them, you have them and she cannot disagree*", while others argued that as the household head and likely providing the capital, men decide whether or not to purchase trees, not their wives.

Table 4.5 Responses from focus group participants to male and female vignettes on the uptake of new technologies.

Women's vignettes – attending a training on a new farming practice		**Men (n = 50)**	**Women (n = 66)**
Consultation	Faith talked to her husband and explained what she had learnt and how it would benefit the farm. He then agreed on trying the new practice and allowed her to make the decisions about it.	76 % (38)	80 % (53)
	Veronica also talked to her husband, but he was not convinced because he did not attend the training. She insisted and after a long discussion the husband finally agreed but he then set the conditions for trying the new practice, like where on the farm and with which crops.	6 % (3)	11 % (7)
No consultation	Margaret had to ask her husband for permission to apply her new knowledge but he refused immediately without further discussion. She could not try the new practice.	12 % (6)	2 % (1)
	Jane went straight to the field and started to try out what she learned. She did not consult anyone	6 % (3)	8 % (5)
Men's vignettes – buying tree seedlings from the local nursery		**Men (n = 54)**	**Women (n = 66)**
Consultation	Alex asked his wife what she thought about buying tree seedlings and which species would be best for their farm and where to plant them.	48 % (26)	42 % (28)
	Peter decided to buy the seedlings on his own but asked his wife about which species would be best for the farm and where to plant them.	33 % (18)	39 % (26)
No consultation	James also decided to buy the seedlings on his own. He came home and informed his wife about the seedlings and where he was going to plant them.	17 % (9)	15 % (10)
	Sammy bought the tree seedlings on his own, came home and planted them. He did not consult anyone.	2 % (1)	3 % (2)

Referring to the vignette with the most votes, we asked participants what would happen should the couple disagree over which tree species to plant. Both men and women commonly explained that when couples disagree, they usually look to negotiate a compromise and would most likely decide to buy half of the trees based on the wife's preferences and the other half based on the husband's choice. One group of men even claimed that they would "*go with the wife's idea* *because she is the one who takes care of management if the husband is not on the farm*". Men and women emphasised that disagreements over farming activities are best avoided since they can lead to the division of household resources, delay time-sensitive activities such as planting, and even result in divorce. Nevertheless, asked what would happen should a disagreement persist, women reported that they would likely "*stay silent*" since their husband, as the household head, has the final say and must be respected.

Men and women reported that disagreements over uptake decisions are often due to only one household member attending workshops, most often the wife. In one group, men stated that "*changing the mindset*" of those who do not attend a workshop can be challenging and that men are "*resistant and reluctant to change when they have not seen [an innovation] work*". Asked how such challenges might be overcome in the future, women proposed that a woman could ask their husbands to choose where on the farm to test the practice. This way, they could see if it worked before scaling to the rest of the farm. A similar solution, closely resembling the PC approach, was also proposed by one group of men: "*they can try the [innovation] on one part of the farm and show the results to convince the one who did not attend. They can do one acre according to the man, one acre according to the woman, and then they see the results*".

3.4 Factors Influencing Women's Agency Over Decisions

Our interviews and FGDs indicated that off-farm employment and outmigration of men influences women's agency over farming decisions. Asked how men and women within their household spend their time when they are not farming, 84% of interviewees reported that men are involved in off-farm income activities, many of whom were reported to work as casual labours in Nairobi or Mombasa. Conversely, only 31% of interviewees reported that women within their household had off-farm income. Several women interviewees reported that their husbands had given them full control over the day-to-day management of the farm in their absence. One woman explained, "*I can call my spouse to discuss farming issues, but he might seem not to understand what I am saying. In such cases I make decisions such as what to plant on what plot, digging of the basins and also terraces*". Women's FGDs also reported that women with husbands who work away tend to exercise greater agency in farming decisions: "*if men are not around, women make the decisions about the [farm], if they are around then they* *consult their husbands*". Yet, several women stressed that they must still consult their absent husbands over the phone.

Women's FGDs reported that their involvement in agricultural workshops had increased in recent years since men now "*go where the money is*". This had contributed to an increase in their influence over farming decisions, with women now more appreciated by their family members because of the knowledge that they gain from attending workshops. Asked how their families reacted the last time they tried an innovation, women recounted direct experiences associated with the basin PC where, once their husbands saw that the basins produced high yields, they had gained more freedom over decisions such as where to dig the basins and what to plant in them. In some cases, women reported being encouraged to try other innovations and receiving additional support from their family members, such as agricultural inputs, money for hiring labour, and assistance with digging the basins.

3.5 Gendered Labour Patterns

Our survey indicated that who was involved in implementing the PCs varied with restoration practice and respondent's gender and marital status (Figure 4.1 and Table 4.6). For married respondents, we saw a higher incidence of both male and female labour having been used to dig basins compared to planting trees, which was a more individual activity. Compared to married men, more women respondents reported that joint labour had been used to implement the PCs. Among married respondents, we also saw a higher incidence of joint labour for watering the trees than planting them, likely reflecting women's greater involvement in tree aftercare. For unmarried men and women, we saw a lower incidence of joint labour for both PCs.

Table 4.6 Gender of those involved in: digging the basins, planting and watering the trees, and preparing land using farmer's usual cultivation practice, grouped by survey respondents' gender and marital status. Statistics presented: count (%) and Fisher's exact test (two-sided).

	Gender of those who provided labour			***p*-value**
	Men only	**Men and women**	**Women only**	
Digging the planting basins				
Married women (n = 331)	36 (11 %)	167 (50 %)	128 (39 %)	< 0.000
Married men (n = 93)	53 (57 %)	40 (43 %)	0 (0 %)	
Unmarried women (n = 52)	8 (15 %)	13 (25 %)	31 (60 %)	---
Unmarried men (n = 3)	2 (66 %)	1 (33 %)	0 (0 %)	
Farmer's usual cultivation practice				
Married women (n = 331)	26 (8 %)	210 (63 %)	95 (29 %)	0.002
Married men (n = 94)	41 (45 %)	51 (54 %)	1 (1 %)	
Unmarried women (n = 50)	5 (10 %)	24 (48 %)	21 (42 %)	---
Unmarried men (n = 3)	3 (100 %)	0 (0 %)	0 (0 %)	
Planting the tree seedlings				
Married women (n = 701)	132 (19 %)	225 (32 %)	344 (49 %)	< 0.000
Married men (n = 359)	305 (85 %)	51 (14 %)	3 (1 %)	
Unmarried women (n = 122)	12 (11 %)	33 (27 %)	75 (61 %)	0.007
Unmarried men (n = 49)	41 (84 %)	8 (16 %)	0 (0 %)	
Watering the tree seedlings				
Married women (n = 678)	22 (3 %)	251 (37 %)	405 (60 %)	< 0.000
Married men (n = 352)	268 (76 %)	78 (22 %)	6 (2 %)	
Unmarried women (n = 124)	8 (6 %)	26 (21 %)	90 (73 %)	0.193
Unmarried men (n = 51)	39 (76 %)	12 (24 %)	0 (0 %)	
Married women				
Digging the basins (n = 331)	36 (11 %)	167 (50 %)	128 (39 %)	< 0.000
Planting the trees (n = 701)	132 (19 %)	225 (32 %)	344 (49 %)	
Married men				
Digging the basins (n = 93)	53 (57 %)	40 (43 %)	0 (0 %)	< 0.000
Planting the trees (n = 359)	305 (85 %)	51 (14 %)	3 (1 %)	

Our survey also showed a higher incidence of female-only and male-only labour used to dig basins compared to farmers' usual cultivation practices (Figure 4.2 and Table 4.6). This was slightly more pronounced for female-only labour suggesting a shift from male to female labour with uptake of basins. Several women FGDs explained that using basins had increased the amount of farm work undertaken by women as, before taking up the basins, they had been less involved in land preparation activities. This trend varied across sites (Figure 4.2). For example, men in Mwala were more involved in digging basins than men in other sites, reflecting that men in Mwala are likely more engaged in farming given the site's relative agricultural potential and market connectivity. Similarly, we saw the largest increase in women's participation in Kibwezi East and Yatta, sites associated with high male outmigration and off-farm employment.

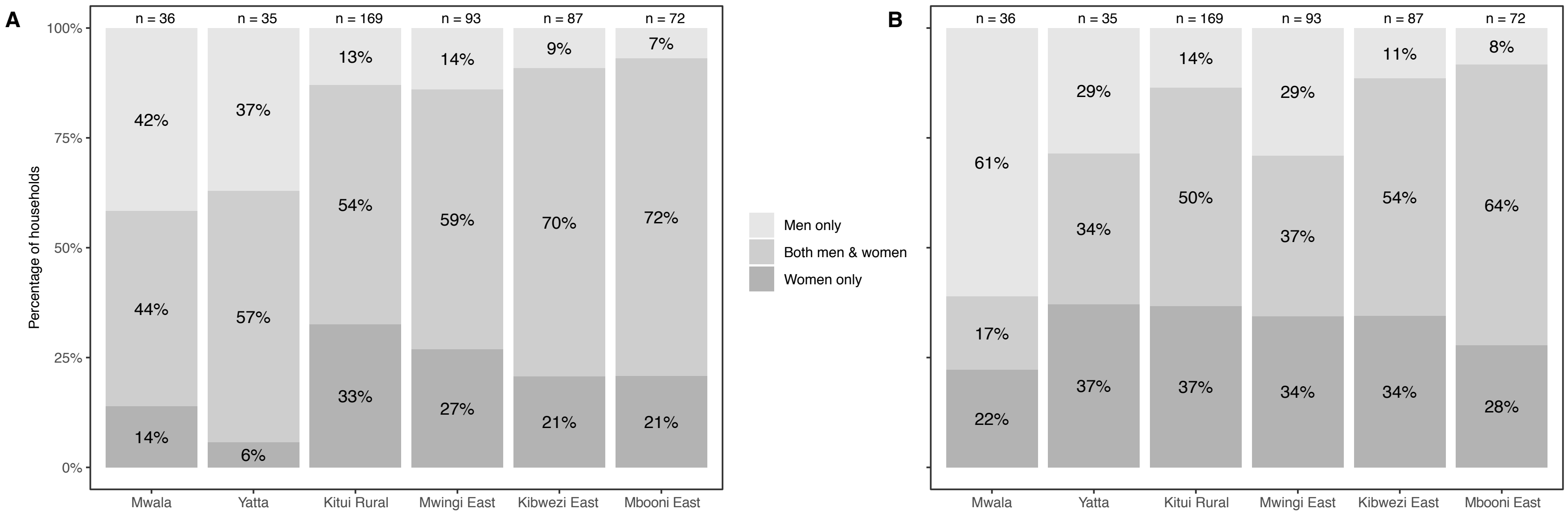


Figure 4.2 Gender of those involved in A) digging the planned comparison planting basins, and B) preparing land using farmer's usual practice.

3.6 Trade-offs Between Workloads and Benefits

Despite the majority of surveyed men and women reporting that using basins had increased the time taken to prepare the land for planting, a sizable proportion reported that using basins had reduced the *overall* amount of time they spend working on their farm (Table 4.7). FGDs and interviewees attributed this to basins requiring less weeding than their usual cultivation practices. FGDs also reported that using basins helps spread labour demand throughout the year since they can be dug throughout the dry season.

Table 4.7 Reported impact of being involved in the tree planting and planting basin planned comparisons on survey respondent's time spent preparing land for planting and their overall amount of time spent working on their farm. Statistics presented: count (%) and Fisher's exact test (two-sided).

	Increased	**Decreased**	**Same**	***p*-value**
Impact of basins on time spent preparing land				
Married women (n = 345)	268 (78 %)	58 (17 %)	19 (6 %)	0.302
Married men (n = 94)	68 (72 %)	17 (18 %)	9 (10 %)	
Unmarried women (n = 44)	37 (84 %)	2 (5 %)	5 (11 %)	---
Unmarried men (n = 3)	1 (33 %)	2 (66 %)	0 (0 %)	
Impact of basins on overall time on farm				
Married women (n = 345)	195 (57 %)	130 (38 %)	20 (6 %)	0.050
Married men (n = 94)	55 (59 %)	28 (30 %)	11 (12 %)	
Unmarried women (n = 44)	24 (55 %)	13 (30 %)	7 (16 %)	---
Unmarried men (n = 3)	1 (33 %)	1 (33 %)	1 (33 %)	
Impact of trees on overall time on farm				
Married women (n = 758)	501 (66 %)	49 (7 %)	208 (27 %)	< 0.000
Married men (n = 382)	300 (79 %)	19 (5 %)	63 (16 %)	
Unmarried women (n = 106)	70 (66 %)	6 (6 %)	30 (28 %)	0.427
Unmarried men (n = 47)	36 (77 %)	1 (2 %)	10 (21 %)	
Impact on overall time on farm: married women				
Planting basins (n = 345)	195 (57 %)	130 (38 %)	20 (6 %)	< 0.000
Tree planting (n = 758)	501 (66 %)	49 (7 %)	208 (27 %)	
Impact on overall time on farm: unmarried women				
Planting basins (n = 44)	24 (55 %)	13 (30 %)	7 (16 %)	< 0.000
Tree planting (n = 106)	70 (66 %)	6 (6 %)	30 (28 %)	
Impact on overall time on farm: married men				
Planting basins (n = 94)	55 (59 %)	28 (30 %)	11 (12 %)	< 0.000
Tree planting (n = 382)	300 (79 %)	19 (5 %)	63 (16 %)	

Although digging basins takes more time than other cultivation practices, both men and women FGDs reported that basins are more productive because of their ability to capture run-off, control erosion and increase soil fertility, and worth the additional time investment, especially when rainfall is limited. Furthermore, women argued that digging basins did not affect their ability to perform other responsibilities since they set aside time to dig them and had formed labour exchange groups to help each other dig the basins (as reflected in Figure 4.1 by the higher incidence of 'group labour' for digging basins).

Another advantage is that basins do not require access to a plough. This may be a particularly important benefit for women since they typically have lower access to resources oxen and ploughing equipment. Our survey reveals that households where only women were involved in ploughing often relied on the use of borrowed equipment and had the lowest rates of plough ownership (Table 4.8). Using basins could benefit women in these households by reducing their dependence on borrowed equipment and helping avoid planting delays.

Table 4.8 Percentage of households who own, borrow or rent ploughing equipment by the gender of those involved in land preparation activities using a plough.

	Plough owned (%)	Plough borrowed (%)	Plough rented (%)
Households where only women are involved in ploughing (n=82)	45	50	5
Households where men & women are involved in ploughing (n=201)	74	18	8
Households where only men are involved in ploughing (n=59)	59	25	15

While the project trees were still young and not yet producing, the main expected benefit and reason for interviewees choosing to plant the tree seedlings was income from fruit and timber sales, followed by increased soil fertility through leaf decomposition and reduced soil erosion. Unlike the basins, the vast majority of survey respondents reported that the tree planting PC had increased the amount of time they spend working on their farm (Table 4.7). Nevertheless, most interviewees reported that since tree planting was a one-day activity with limited follow-up, their involvement in the PC had not impacted their ability to perform other activities. The majority of survey respondents, regardless of gender and marital status, reported that over the next 12 months they planned to dig more basins and plant more trees on their farm (Table 4.9). Reasons for not digging more basins or planting more trees centred on labour and financial constraints, respectively (Table 4.10).

Table 4.9 Whether survey respondents planned to dig more basins or plant more trees in the next 12 months. Statistics presented: count (%) and Fisher's exact test (two-sided).

	Yes	***p*-value**
Do you plan to dig more planting basins next season?		
Married women (n = 345)	304 (88 %)	0.856
Married men (n = 94)	84 (89 %)	
Unmarried women (n = 44)	37 (84 %)	---
Unmarried men (n = 3)	1 (33 %)	
Do you plan to plant more trees next season?		
Married women (n = 758)	571 (75 %)	0.770
Married men (n = 382)	291 (76 %)	
Unmarried women (n = 106)	83 (78 %)	0.677
Unmarried men (n = 47)	35 (74 %)	

Table 4.10 Ten most frequently used words by survey respondents when explaining why they did not intend to dig more planting basins (n=60) or plant more trees (n=316).

Tree planting		**Planting basins**	
Word	**Frequency**	**Word**	**Frequency**
Lack	103	Labour	19
Money	78	Intensive	11
Water	68	Time	11
Maintain	48	Season	8
Purchase	46	Consuming	6
Capital	43	Dig	6
Lacks	40	Man	6
Seedlings	31	Power	6
Buy	28	Tedious	6
Funds	28	Lack	5

4. Discussion

Three key insights emerge from our study. First, that in married households, the uptake of restorative farming practices is generally not a unitary decision made by individuals acting alone but involves some form of consultation between husband and wife. Secondly, that multiple social dimensions intersect to shape men's and women's interest in, contributions to, and benefit from different restoration practices. These include the gender-related roles and norms surrounding the use and control of household resources and outputs from innovations and vary with local socio-economic context. And finally, that the intrahousehold dynamics that underpin adoption processes, are in turn shaped by women's increasing involvement in innovation processes and broader societal changes, particularly the outmigration of rural men. In the following section, we discuss these three insights and their implications for scaling-up on-farm restoration in eastern Kenya and set out several recommendations for more inclusive and gender-responsive restoration efforts.

4.1 Intrahousehold Approaches to On-farm Restoration

Based on our findings, we argue that in the eastern drylands of Kenya, employing an intrahousehold approach to restoration is likely to increase both the uptake of restoration practices and the success and equity of on-farm restoration efforts. A common assumption in agricultural development is that the household head, often a man, is the primary decision-maker over farming-related activities. Our study challenges this notion and illustrates that, at least in eastern Kenya, decisions over the uptake of restorative farming practices are often initiated by women and usually involve some form of consultation between husband and wife. These findings further contribute to growing evidence that households in SSA often employ different decision-making dynamics with varying degrees of consultation, and that the household head is not always the sole decision-maker (Doss and Meinzen-Dick, 2015; Doss and Quisumbing, 2020; Meijer et al., 2015).

Assumptions about who is involved in uptake decisions are likely to have important implications for the uptake of on-farm restoration efforts. Although our study only included those who had implemented the PCs, our findings indicate that the uptake of restoration practices may be constrained by the fact that only one household member usually attends training workshops, and that women can find it challenging to persuade their husbands of the potential benefits from an innovation. Restoration projects engaging only one household member without considering the whole household and all of those involved in uptake decisions may be constraining greater uptake of restoration practices. Consequently, we recommend that initiatives aiming to restore degraded farmlands identify clearly who within the household is involved in uptake decisions. Furthermore, while our surveys and interviews included only one member from each household, recent studies indicate that interviewing both spouses within a household can provide a richer and more nuanced understanding of intrahousehold decision-making dynamics (Acosta et al., 2019; Ambler et al., 2019; Bernard et al., 2020).

Who is involved in uptake decisions is also likely to influence the success and sustainability of restoration efforts. For instance, several studies indicate that joint decision-making between husband and wife over tree planting is associated with higher densities of on-farm trees than when decisions are made alone (Meijer et al., 2015; Wanyoike, 2001). As argued by Kiptot and Franzel (2012) and supported by our findings, this is likely partially explained by both husband and wife on jointly managed farms providing labour for tree establishment. Similar to Shibata et al. (2020), we found that men's and women's involvement in uptake decisions was strongly related to their labour contributions in implementing and managing an innovation. In our study, consultation was seen, especially by men, as a means of assuring buy-in from other household members and securing the success of an innovation, as illustrated by spousal consultation being perceived as critical for successful tree establishment since women are heavily involved in caring for young trees.

Men's and women's participation in implementing an innovation is also likely to influence their authority over the resulting outputs (e.g., crops and income), and thus the distribution of benefits from on-farm restoration efforts (Shibata et al., 2020). To increase both the uptake of practices and the success and equity of on-farm restoration efforts, we recommend that initiatives employ an intrahousehold approach, and look to encourage joint decision-making and couple attendance at workshops and, in situations when couple attendance is not possible, provide women with additional training in negotiation skills. Furthermore, the PC approach was proposed by study participants as a potential mechanism for negotiating the tryout of an innovation. Encouraging on-farm experimentation could thus provide a potential pathway to engaging the wider household in on-farm restoration activities and increasing uptake.

4.2 Gendered Interests, Contributions and Benefits from Restoration

We recommend that initiatives seek to understand the gender roles and relations that underpin different groups of men's and women's access and control of household resources, and thus their interest in, contribution to, and benefit from different restoration practices. In our study, men's and women's authority over uptake decisions were shaped by gender norms surrounding the use and control of resources and outputs from restoration practices. For instance, women's greater interest and authority over the basin PC likely reflects that basins are associated with growing food for the family, a domain generally seen as a woman's responsibility. Similarly, men's greater interest and self-decision over the tree planting PC likely reflects customary norms surrounding land and tree tenure (Kiptot and Franzel, 2012).

In SSA, men typically have greater authority over land and agricultural enterprises that generate high revenues (Njuki et al., 2011). This includes agroforestry enterprises involving high-value products (Kiptot and Franzel, 2012). Although the project trees were still young and not yet producing, most seedlings planted were of species with high commercial value for fruit or timber, potentially further explaining men's greater interest and involvement in the tree planting PC compared to the basin PC. Given that men's and women's rights over land and trees shape their incentives to plant trees and invest in land-based measures (Lovo, 2016; Meinzen-Dick, 2006; Mukadasi and Nabalegwa, 2007), it is essential that restoration initiatives identify the key gender-tenure interactions within a locality, and how these relate to the uptake different innovations and the distribution of benefits within the household, and thus gender-equitable outcomes.

Our study also reveals that intrahousehold decision-making and labour dynamics vary with marital status and male absence associated with off-farm employment and outmigration. These findings contribute to a growing awareness that multiple social dimensions intersect with gender to shape men's and women's interest in, contribution to, and benefit from agricultural innovations (Carr and Thompson, 2014), including age and position in household (Crossland et al., 2021; LaRue et al., 2021), wealth (Shibata et al., 2020), and kinship structures (Meijer et al., 2015). Understanding these social dimensions begins with conducting gender analysis of restorative farming practices. For instance, initiatives could look to integrate tools from existing assessment methodologies into project activities, for example, tools from the INGENAES toolkit (Manfre et al., 2017), GENNOVATE methodology (Petesch et al., 2018), or other gender-transformative approaches (FAO et al. 2020).

Furthermore, similar to other studies (Baudron et al., 2007; Nyanga et al., 2012), we found evidence that using basins can alter when associated farming activities occur (i.e., land preparation), how long they take (i.e., weeding) and who is involved. Nevertheless, despite a potential increase in their labour burden, women perceived digging basins to be worthwhile. These findings highlight the importance of understanding how restoration efforts influence the men's and women's workloads, but also how farmers perceive and value their time and benefits from these practices (Njuki et al., 2014; Theis et al., 2018). While quantitative approaches to cost-benefit analysis might conclude that the time spent digging basins is not worthwhile, farmers, especially women, may value costs and benefits differently and perceive that the benefits outweigh the labour requirement. We thus recommend that initiatives conduct gender analysis of innovations not only during their design but also following their uptake and include the views and perceptions of project beneficiaries when assessing the costs and benefits from restoration activities.

4.3 Changes in the Wider Social Context of On-farm Restoration

As our study demonstrates, the intrahousehold roles and relations underpinning adoption processes are, in turn, shaped by women's increasing involvement in agricultural innovation and broader societal changes, particularly the outmigration of rural men. In line with a growing literature (Chant and Radcliffe, 1992; Saha et al., 2018; Yabiku et al., 2010), our findings show that women with migrant husbands often have greater agency over farming decisions than women with resident husbands. Furthermore, we found that women are heavily involved in uptake decisions, including those regarding tree planting, and that even women with resident husbands may be able to contest restoration decisions. These findings challenge the narrative that men in eastern Kenya are the chief decision-makers over farming and tree planting (Kiptot et al., 2014; Muok et al., 1998), and likely reflect women's increased participation in agricultural workshops and farm management in the absence of their male relatives (Crossland et al., 2021). Similar to other studies, our findings indicate that when women attend agricultural workshops and are allowed to implement their knowledge, they gain more confidence and recognition that can lead to greater agency in farming decisions (Bullock and Tegbaru, 2019; Nyasimi and Huyer, 2017).

Nevertheless, while women may be gaining agency over farming decisions, there is rising concern that male outmigration may result in negative consequences for women's welfare (Saha et al., 2018). For instance, the absence of male members during peak farming periods may increase agricultural workloads for women and reduce time available for household tasks and child care (Slavchevska et al., 2016). Given that on-farm restoration efforts are often labour-intensive, their promotion in regions experiencing increasing male outmigration risks placing the burden of restoration disproportionally on women. While beyond the scope of this study, the impact of male outmigration on the capacity of rural households to restore degraded lands is thus a pressing issue for future research.

Our findings also illustrate that, if on-farm restoration efforts are to meet both social and ecological objectives, deliberate actions may be needed to further shift gender relations in a direction that increases women's agency in respect of farming decisions. Despite women's increased involvement in workshops and uptake decisions, it is evident that asymmetries in decision-making authority persist. Women's ability to implement innovations across the farm largely depended on some form of pro forma consultation with their husbands and even women with absent husbands were often still obligated to consult their spouse. These findings are similar to other studies in SSA, including those conducted elsewhere in Kenya (Acosta et al., 2019; Bullock and Tegbaru, 2019; Shibata et al., 2020). It is also worth noting that most women involved in our study were older, married and had access to land. Our results thus likely overlook considerable variation in the experiences of different groups of women, with older women likely better able to negotiate access to land, influence decisions and have more free time to attend agricultural workshops than younger women (Rietveld, 2017).

While women's participation in agricultural workshops alone is unlikely to transform entrenched gender norms, integrating deliberate actions to address inequitable gender relations in project design and implementation, show promise (Cole et al., 2020; Kantor et al., 2015; Lecoutere and Wuyts, 2020). For instance, in Uganda, a research project employing participatory approaches that aimed to address gender inequalities, resolve conflict and foster collaboration and negotiation, is reported to have achieved substantial gains in strengthening women's rights to forest and tree resources and their inclusion in community forestry decisions (Mukasa et al., 2016). Through integrating gender-transformative approaches and using project activities to facilitate critical awareness and discussion of gender-inequitable relations, we argue that initiatives could not only overcome gender-based constraints to scaling-up on-farm restoration efforts but provide a platform for social learning and the transformation of inequitable gender relations within households and the wider community.

5. Conclusion

In this study, we demonstrate that successful restoration activity in the eastern drylands of Kenya will only be achieved with careful consideration of how gender dimensions feed into decision-making. This requires understanding the intrahousehold dynamics surrounding innovation uptake and the distribution of resulting benefits. We argue that employing an intrahousehold approach to restoration is likely to increase both the uptake of practices and the success and equity of on-farm restoration efforts. We recommend that restoration initiatives seek to understand the gender roles and relations that underpin different groups of men's and women's access to and control of household resources, and thus their interest in, contribution to, and benefits from different innovations. Our findings illustrate the importance of understanding intrahousehold decision-making patterns and that, if on-farm restoration efforts are to meet both social and ecological objectives, deliberate actions may be needed to shift gender relations in a direction where women have increased voice over farming decisions.

Chapter 5: Exploring Women's Changing Opportunities and Aspirations Amid Male Outmigration

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1. Introduction

Developing and scaling new agricultural technologies is widely considered an essential pathway for increasing the productivity of smallholder agriculture in low-income countries and to achieving the UN's Sustainable Development Goals of ending poverty and hunger (Pingali et al., 2006; Vorley et al., 2012). Yet, despite significant investment from governments, researchers and international development agencies, changes in agricultural practices over the past decade have been slow (Thornton et al., 2018), with numerous cases of low adoption by smallholder farmers of seemingly productive and profitable technologies (e.g., Arslan et al., 2013; Chirwa, 2005; Walker and Alwang, 2015).

Development-focused agricultural researchers have paid considerable attention to identifying the factors that constrain or enable the uptake of new innovations, resulting in an extensive list of adoption-related variables (Feder et al., 1985; Mwangi and Kariuki, 2015). These tend to centre on observable characteristics such as a farmer's access to information, markets and complementary inputs and resources, including land, labour, capital and credit. Less attention, however, has been paid to internal factors that drive adoption decisions, such as a farmer's attitudes, preferences and motivations. Even when such factors are considered, they are rarely understood in the broader livelihood context that, for many smallholder households, often includes non-agricultural components.

Given the seasonal, risky nature of farming, the inherent limitations of small farm size and the prevalence of severe land degradation, rural households in sub-Saharan Africa rarely rely on farming alone and increasingly pursue diverse livelihood strategies comprising various on- and off-farm activities and income streams in order to survive (Barrett et al., 2001; Harris and Orr, 2014). Consequently, decisions over resource allocation and investment often involve complex trade-offs between multiple livelihood activities (Giller et al., 2006). While households may derive part of their livelihood from farming and personally identify as farmers, agricultural production is unlikely to be the only aspect of their livelihood portfolio they are seeking to maximise. Indeed, many households may seek to step out of farming completely and focus on local or migratory off-farm income sources (Dorward et al., 2009).

In recognition that people's desired futures likely play an important role in influencing their investment decisions, there is a small yet growing literature arguing for greater consideration of livelihood aspirations[16] in the design and targeting of development-focused agricultural research (Dilley et al., 2021; Dorward et al., 2009; Mausch et al., 2021, 2018; Verkaart et al., 2018). Both Mausch et al. (2018) and Verkaart et al. (2018) contend that, in addition to current livelihood portfolios, an understanding of people's *aspired* livelihood activities could inform a more targeted and efficient approach to rural development.

Through understanding people's current situations, desired trajectories and the influences that shape these aspirations, researchers and development actors might tailor support options[17] to better meet the needs of different user groups by matching technologies to peoples' strategies and demands (Mausch et al., 2018). For example, within the Dorward et al. (2009) framework, people who see farming as their main occupation and aspire to 'step up' their farming activities are likely to be more willing to invest in longer-term and/or more financially intensive options, such as agroforestry, land restoration or irrigation technologies. Innovations around markets and commercialisation are also likely to be better received. For those who do not see a future in farming and want to 'step out' and pursue non-farm income sources or even migrate to urban areas, labour-saving agricultural technologies, loans and training in non-farm skills may be more appropriate. For those who are net buyers of staple food crops and lack alternative options to farming or still hope to be able to 'step-up' at some point and are therefore 'hanging in', agriculture could provide an important safety-net. Given their lack of resources, innovations aimed towards social protection and food security (e.g., providing inputs such as seeds, food assistance or low-cost innovations) are likely to be important for this group. Understanding people's current circumstances and livelihood aspirations could enable agricultural research and development initiatives to better serve the wants and needs of rural populations.

This is not to say that agricultural research and development do not have a role in addressing the underlying causes for farmers choosing to 'step out' and divest from farming. For example,

[16] While aspirations-based theories in economics have largely focused on people's 'capacity to aspire' (Appadurai, 2004), or rather their level of ambition relative to those around them, we use the term 'aspiration' to refer to what people *aspire to do,* with specific attention to the livelihood activities with which they wish to engage (Mausch et al., 2018).

[17] Although systems of innovation emerge from different and often interrelated forms of knowledge (Glover et al., 2019), our focus in this study is the role of aspirations within processes of technological change driven by external institutions, rather than those arising from farmers' own experimentation and experience.

in addressing low agricultural productivity and land degradation which undermine a household's ability to generate returns beyond the poverty line. Nevertheless, focusing efforts on areas and groups where they are potentially most valuable and appreciated is likely to make better use of limited resources and, ultimately, have greater impact on poverty and food security (Gassner et al., 2019).

The concept of 'opportunity spaces' has recently been used to conceptualise the formation of aspirations (Elias et al., 2018; Rietveld et al., 2020). An 'opportunity space', as defined by Sumberg et al. (2012), is "the spatial and temporal distribution of the universe of more or less viable options that a young person may exploit as she/he attempts to establish an independent life". The topology of a person's opportunity space is first a function of the physical realities in which they live and includes climate, geography and market availability. A person's ability to explore and exploit this space is then further mediated by social factors including social identity, norms and relations (Sumberg and Okali, 2013). Age and gender are important and intersecting social dimensions in structuring people's position in society, their access to, and control of, agricultural assets and resources and thus men's and women's livelihood possibilities throughout life (Meinzen-Dick et al., 2012). Yet, recent studies on rural aspirations in relation to agriculture have largely focused on the aspirations of young men and women (Elias et al., 2018; Rietveld et al., 2020) or overlooked gender and position in household completely (Verkaart et al., 2018). In this preliminary study, we attempt to shed light on the role of intrahousehold dynamics in shaping men's and women's opportunity spaces and aspirations and how they evolve throughout life.

Consideration of the intrahousehold relations that underpin men's and women's livelihood strategies and aspirations are increasingly pertinent with intensifying migration trends across sub-Saharan Africa. Where local labour markets are inadequate and farms insufficient in size and quality to ensure a reliable livelihood, household members seek to diversify their income streams through migratory wage labour, leaving their homesteads for extended periods of time (Mercandalli et al., 2020). Due to economic and social factors, these mobilities are often gender-specific, with male household members often being those who leave (Chant and Radcliffe, 1992). Resultant changes in household structures can lead to redistribution and redefinition of household responsibilities, with women often assuming the role of primary farmer (Yabiku et al., 2010). This reconfiguration of responsibilities can increase both the physical and emotional burden on women, but equally give women greater agency over household and farming decisions in ways that allow them to further their wants and needs (Saha et al., 2018; Slavchevska et al., 2016; Yabiku et al., 2010).

It is against this backdrop of outmigration and feminisation of agriculture that we frame our study around men's and women's changing opportunity spaces in the drylands of eastern Kenya and attempt to shed light on the dynamics of rural aspirations in relation to both gender and age. Using a novel methodology combining short narratives with semi-structured interviews and focus group discussions (FGDs), we contribute to a more nuanced understanding of aspirations and the wider socio-cultural context within which they are embedded and make several recommendations for progressing aspirations research.

2. Methods

Data consisted of 138 short aspirational narratives from 88 women and 50 men living in Makueni County, Kenya, and was supported by several additional co-located datasets from a land restoration project, including four FGDs on men's and women's agency, two FGDs on local migration trends, and 12 semi-structured interviews with women from households with migrant members (Figure 5.1).

2.1 Study area

Makueni County, located in a semi-arid area of south eastern Kenya, is characterised by small-scale rainfed agriculture and experiences frequent drought and crop failures due to increasingly erratic and unreliable rainfall (KNBS 2019). Due to subdivision of land and population growth, farms are small with an average farm size of 1.2 hectares (GoMC 2018). Agricultural productivity is further limited by widespread land degradation in the form of soil erosion and low inherent soil fertility. Consequently, there are high levels of both poverty and food insecurity (KFSSG, 2019). With marginal farming conditions and insufficient off-farm employment opportunities locally, many people, particularly men, are increasingly choosing to migrate in search of employment to nearby towns or larger urban areas such as Nairobi and Mombasa (GoMC 2019; Ifejika Speranza, 2006).

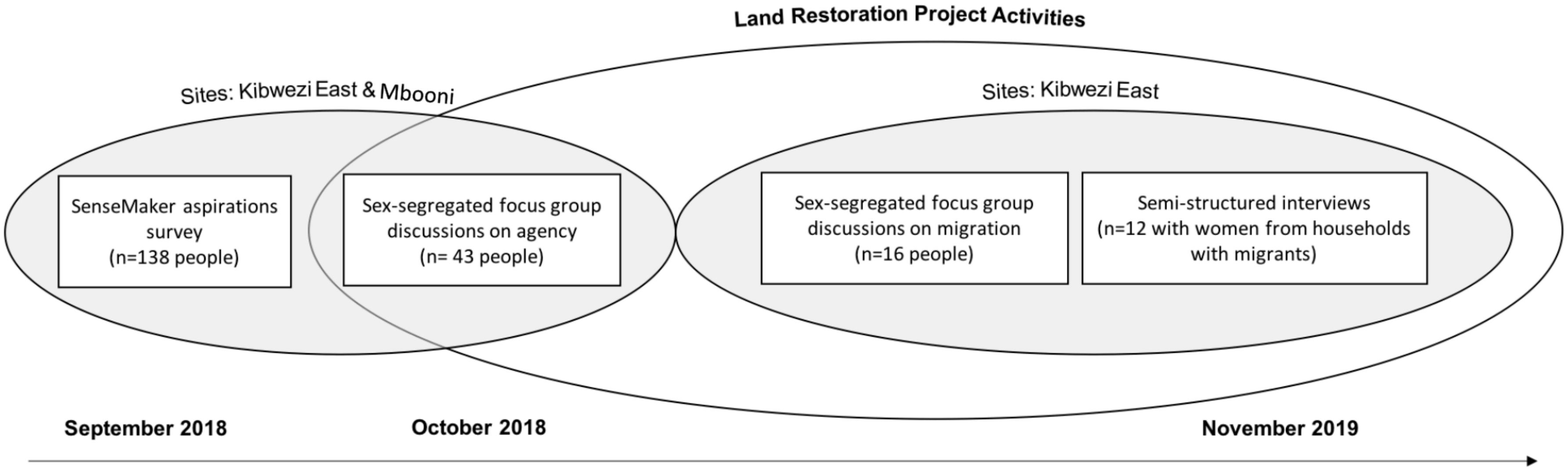

Figure 5.1 Overview and chronology of methods.

Intrahousehold roles and relations in the area remain predominantly governed by patriarchal norms, with the husband seen as the head of the household and breadwinner and the wife as the carer of the home and children (Ifejika Speranza, 2006). Despite Kenya's constitution granting men and women equal rights to inherit and own land, in practice, women's land rights remain restricted by customary practices whereby women rarely inherit land themselves and typically attain secondary use rights through their husband following marriage (Musangi, 2017). Men therefore tend to have greater access to and control over land and, in turn, a greater social legitimacy with regards to decisions about agricultural activities and income (Dolan, 2001).

2.2 Aspirations survey

The first phase of data collection involved SenseMaker®, a narrative-based survey tool, whereby respondents tell a short story in response to an initial prompting question and then interpret their narrative using a set of predefined self-assessment questions (Cognitive Edge, 2020; Mausch et al., 2018). While the SenseMaker® tool has been used to explore complex social issues including people's understandings of climate change adaptation (Lynam and Fletcher, 2015), it has not been used in the analysis of rural aspirations. This exploratory study is a first attempt to use it to capture aspirations and was conducted as part of a wider project exploring its application in operationalising livelihood aspirations for rural development (Mausch et al., 2021).

To capture individual's envisioned futures, we asked respondents: "Imagine your life in 10 years' time, tell a story about how you got to that point from this present day?". This opening question was intended to evoke an unrestricted response and deliberately did not mention farming or non-farming activities. Respondents were then asked to interpret their stories or narratives using a set of predefined assessment questions[18]. In this paper, we focus on the narratives themselves and a subset of self-assessment questions designed to explore men's and women's attitudes towards farming, the degree to which they feel they have opportunities in life, and their perceived confidence in achieving their aspirational goals (Figure 5.2). This subset of questions included the use of dyads, where respondents rate their narrative using a sliding-scale between two opposing statements (resulting in a score between 0 and 100), an

[18] See Mausch et al. (this issue) for full description of the SenseMaker® survey.

open-answer question on how they spend their time when they are not farming, and several multiple-choice questions regarding demographic characteristics of the respondent (i.e., age, gender and position in household). The survey was conducted in September 2018 by a team of trained enumerators recruited from Makueni and administered using tablets. Each respondent was surveyed in private, and their story translated and transcribed into English before being asked to interpret their story using the self-assessment questions.

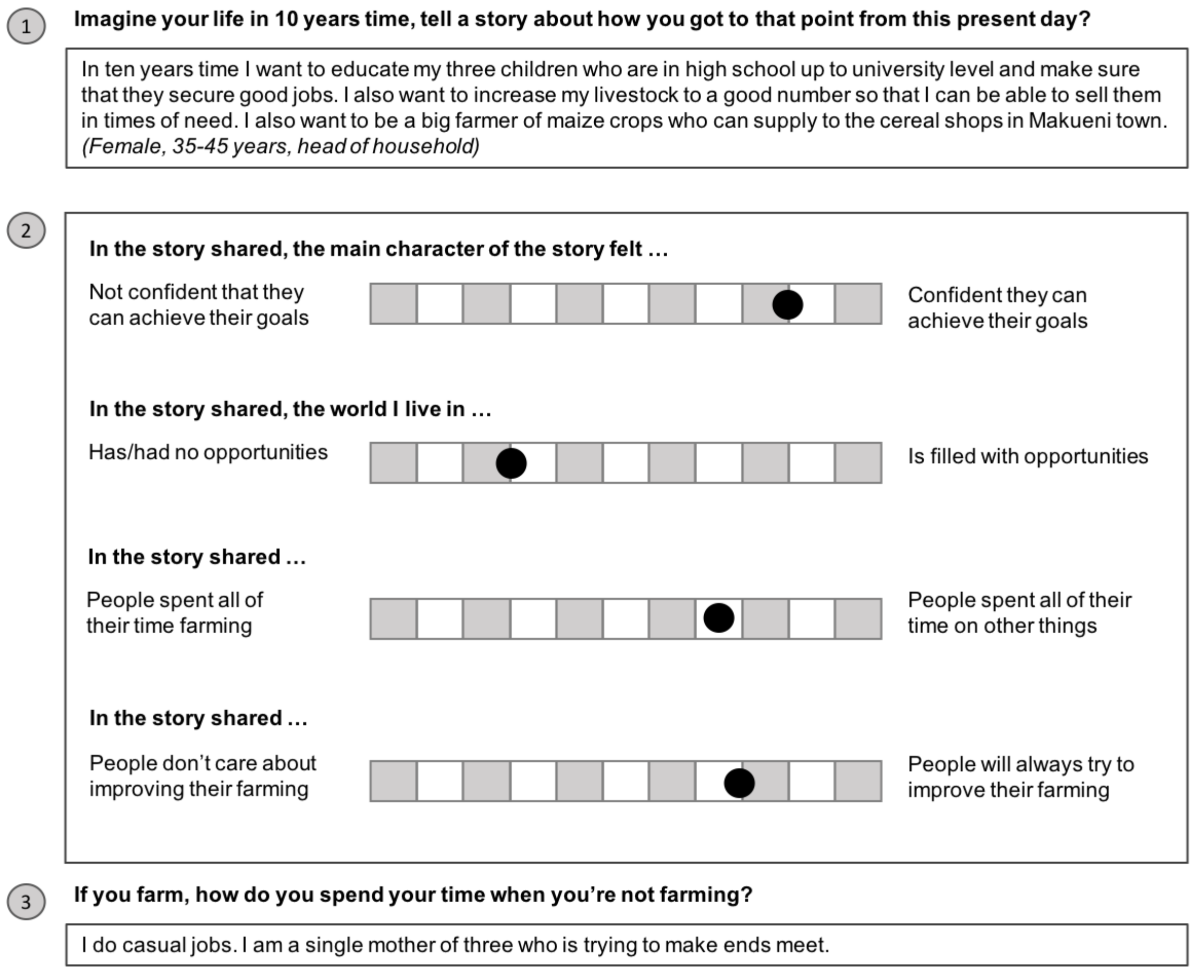

Figure 5.2 Example responses to opening question (1), self-assessment dyads (black dot) (2) and follow-up question (3) used in the SenseMaker survey tool.

Survey locations were co-located with the activities of a five-year land restoration project working with 645 farmers across two sites located in Makueni County: Kibwezi East and Mbooni constituencies (World Agroforestry, 2020) (Table 5.1). This allowed us to draw on several additional qualitative datasets collected by the project within the same rural communities. For the aspirations survey participants, a sampling frame was utilised whereby ten villages were randomly selected and from each village, ten households were randomly selected from the village roster. In each household, the household head was surveyed followed by either their spouse or a child based on random selection. No replacements were made for unavailable respondents. This sampling procedure resulted in a total of 138 storytellers across a range of age groups and positions within the household (Table 5.1). The resulting sample however shows a bias towards women and older age groups since men and youth were often unavailable to take the survey (i.e., children were in school, and men had migrated or were working off-farm during the time of interview).

2.3 Focus group discussions and semi-structured interviews

The second phase of data collection involved FGDs on agency, intrahousehold gender relations and local migration trends, and semi-structured interviews with women from households with migrant members. These field activities were co-located with the aspirations survey and provided additional information on the social context within which men's and women's aspirations were embedded.

The first set of FGDs were held in October 2018 in both Kibwezi East and Mbooni (a total of four groups, two with women only and two with men only). One of the aims of these discussions was to explore recent changes in women's agency understood as the "ability to define one's goals and act upon them" (Kabeer, 1999 p. 438). We used an adapted version of the 'Ladder of Power and Freedom' ranking exercise described in Petesch et al. (2018). This involved asking participants to vote, in private, on which step of a five-step ladder best represented the majority men and women in their community in terms of their current level of agency and that of five years ago (i.e., 2013), and then discussing the reasons for men's and women's movement, if any, up or down the ladder. A five-year period was chosen instead of the ten-year period used by Petesch et al. (2018) to improve recall.

An additional round of FGDs was held in November 2019 in Kibwezi East (two groups, one with women only and one with men only) to explore gender-specific migration trends and drivers and recent changes in opportunities in agriculture. Twelve semi-structured individual interviews were also conducted with women from households with migrant members. These interviews covered similar topics to the FGDs but focused on women's personal experiences and those of migrant household members.

Table 5.1 Characteristics of farmers engaged in the land restoration project and SenseMaker aspirations survey respondents.

	Land restoration project			SenseMaker aspirations survey		
	Men (n=143)	Women (n=502)	All (n=645)	Men (n=50)	Women (n=88)	All (n=138)
Relation to household head[1]						
Household head	--	--	--	47 (94%)	27 (31%)	74 (54%)
Spouse	--	--	--	0 (0%)	59 (67%)	59 (43%)
Child	--	--	--	3 (6%)	2 (2%)	5 (4%)
Marital status[1]						
Married	119 (83%)	417 (84%)	536 (83%)	--	--	--
Divorced	2 (2%)	13 (3%)	15 (2%)	--	--	--
Widowed	6 (4%)	47 (9%)	53 (8%)	--	--	--
Single	16 (11%)	25 (5%)	41 (7%)	--	--	--
Age group[1]						
Under 25	7 (5%)	18 (4%)	25 (4%)	3 (6%)	5 (6%)	8 (6%)
25-34	13 (9%)	103 (21%)	116 (18%)	7 (14%)	17 (19%)	24 (17%)
35-44	38 (27%)	145 (29%)	183 (28%)	9 (18%)	26 (29.5%)	35 (25%)
45-54	35 (24%)	144 (29%)	179 (28%)	9 (18%)	14 (16%)	23 (17%)
Over 54	50 (35%)	92 (18%)	142 (22%)	22 (44%)	26 (29.5%)	48 (35%)
Farm size (hectares)[2]						
Under 25	3.3 (2.4)	2.4 (1.5)	2.7 (1.7)	6.6 (8.3)	1.2 (0.6)	3.2 (5.3)
25-34	5.6 (10.0)	2.7 (2.2)	3.0 (4.0)	1.6 (1.7)	2.9 (4.8)	2.5 (4.1)
35-44	5.7 (8.7)	4.1 (5.1)	4.4 (6.0)	2.4 (1.4)	2.6 (3.3)	2.5 (2.9)
45-54	3.6 (4.0)	4.2 (4.3)	4.1 (4.3)	4.2 (4.7)	4.4 (4.6)	4.3 (4.6)
Over 54	7.1 (8.4)	6.4 (10.9)	6.6 (10.1)	8.5 (9.4)	5.6 (7.7)	6.9 (8.5)
All ages	5.5 (7.6)	4.2 (6.1)	4.5 (6.5)	4.4 (7.3)	3.8 (5.4)	4.4 (6.2)
Household size[2]						
Under 25	6.1 (1.2)	4.4 (1.7)	4.9 (1.7)	8.7 (2.1)	4.4 (2.3)	6.0 (3.0)
25-34	4.6 (2.0)	5.1 (3.3)	5.1 (3.2)	3.9 (0.4)	3.9 (0.6)	3.9 (0.5)
35-44	5.6 (1.5)	5.6 (1.5)	5.6 (1.5)	4.8 (2.0)	4.9 (1.4)	4.9 (1.6)
45-54	6.4 (1.9)	6.5 (2.2)	6.5 (2.2)	4.7 (2.3)	3.5 (2.1)	4.0 (2.2)
Over 54	6.1 (3.1)	6.4 (2.8)	6.3 (2.9)	4.3 (2.9)	4.0 (2.2)	4.1 (2.5)
All ages	4.4 (1.5)	5.8 (0.9)	5.9 (2.5)	4.7 (2.5)	4.2 (1.8)	4.4 (2.1)

[1] Statistics presented: n (%)
[2] Statistics presented: mean (SD)

For both sets of FGDs, random purposive sampling was used to select male and female participants from a list of farmers registered with the land restoration project and to ensure representation of men and women involved in different project interventions. For the migration FGDs, random purposive sampling was employed to enrol men and women from households with and without migrant members (Table 5.2). Group sizes ranged from 5-22 participants with a total of 14 men and 29 women in 2018, and 8 men and 8 women in 2019. For the semi-structured interviews, 12 women were purposively selected from project households to represent a range of different household situations, including women with migrant sons, husbands and daughters (Table 5.2). Age was not a selection criterion for the FGDs or interviews as the majority of farmers participating in the project are within a certain age range (50% of participants are aged 35-53). Although age was not an explicit consideration in our selection criteria, participant ages ranged from 34 to 70 years in the FGDs and 37-56 years in the interviews (Table 5.2).

Table 5.2 Participant characteristics for migration focus group discussions (FGDs) and semi-structured interviews.

	Migration FGDs		Migration interviews
	Men (n=8)[3]	Women (n=8)	Women (n=12)
Age[1]	38.8 (4.7)	43.4 (11.3)	46.6 (6.1)
Farm size (hectares)[1]	10.9 (16.4)	10.4 (13.3)	2.9 (3.1)
Household size[1]	4.4 (1.5)	5.75 (0.9)	5.8 (1.4)
Marital status[2]			
Married	4 (80%)	7 (88%)	10 (83%)
Divorced/widowed	1 (20%)	1 (12%)	2 (16%)
Migrant(s) relation to household head[2]			
Themselves/household head	2 (17%)	0 (0%)	0 (0%)
Spouse	0 (0%)	4 (50%)	9 (75%)[4]
Son	0 (0%)	1 (12%)	11 (92%)
Daughter	1 (13%)	1 (12%)	5 (42%)
No migrants	6 (75%)	3 (37%)	--

[1] Statistics presented: n (%)
[2] Statistics presented: mean (SD)
[3] Missing data for three male participants.
[4] Two husbands were retired migrant workers and four worked locally, returning home each evening.

2.4 Data analysis

Qualitative analysis was conducted using NVivo 11 software (QSR International, 2015). Narratives from the aspirations survey were first deductively coded for content analysis based on whether they mentioned farming or non-farming related aspirations or both. Additional codes were then developed inductively based on thematic analysis and cross-case comparisons conducted with respect to gender and age. Dyad self-assessment questions were analysed in the R software environment (R Core Team, 2020) and the Wilcoxon rank-sum test used to compare responses from respondents. Textual data from the FGDs and interviews were inductively coded based on responses and dominant topics raised by participants.

3. Results

3.1 Migration trends and drivers

During our FGDs on migration, both men and women reported that migrants from their community tended to be younger adult men, leaving to find casual jobs in cities, such as Nairobi or Mombasa, or to work as labourers on large farms. These migrants generally returned home weekly or monthly to visit their families but usually for only a few days at a time.

The main reason given by interviewees for the migration of household members was to earn additional income and support their families. Migration was seen as part of a household strategy, with an individual's decision to migrate often having been discussed and decided on as a household. Several women, for example, reported involvement in their son's decision to migrate, allowing them to leave so that they could support the family financially. Some had even funded their children's migration using their savings or through selling livestock.

It was also mentioned that young men may leave if their parents' farm is small and they do not have land to farm. However, several women indicated that young people lacked an interest in farming. One explained that, while her migrant son aspires to farm and continues to keep cattle, young people, in general, do not like farming since it is "*not a prestigious and professional job*". Another reported that her migrant son had previously been involved in farming "*but became lazy due to the [poor] rain*". One woman also stated that her son had applied for a job immediately after finishing school since "*anyone who has finished school is supposed to get a job*".

During the FGDs, men reported that while many of the male migrants in their community were still young, they expected that most would return to the community in their retirement. Although none of the women interviewees reported that they or their families planned to join their migrant members, six anticipated that their migrant sons would one day move back to their village permanently, and two expected their husbands would return permanently once they retire. Both groups reported that the number of adult men leaving had increased over the past five years due to deteriorating climatic conditions and increasingly poor rainfall.

Although still a minority, participants reported that the number of unmarried women leaving in search of work had also increased. However, both groups agreed that women, and in particular those who are married, have fewer opportunities to migrate and are expected to stay and look after the home and children. Several men joked that there is a fear that a married woman will "*get into bed with a man who drives a black car*", implying she may find another husband with a more stable income. They also argued that it is risky for women to migrate since they may find themselves homeless while searching for work; a situation that men are more capable of navigating given that they can sleep *"in a ditch beside the road*", while a woman cannot.

3.2 Men's and women's agency and opportunities in agriculture

During the Ladder of Power and Freedom exercise, women participants indicated a substantial increase in agency over the past five years (Figure 5.3). Reasons for these changes included increased awareness of women's rights through constitutional changes and seminars, the outmigration of men, and women's increased participation in agricultural training. While women were said not to have been valued five years ago with men having made all major decisions, farming and household decisions now tend to be discussed and made together as a household. Women reported that agricultural training events now include both men and women and that through these engagements, men had seen that women are capable of contributing ideas and carrying out tasks typically assigned to men, such as terracing and fencing. Women also stated that it is now common for men to work outside the homestead and so women have more freedom to make decisions independently. One woman gave the example that her migrant husband was unaware she was attending the FGD and that she was the one who has to decide what is best for the family while he is away. Nevertheless, several women emphasised that a woman must still respect her husband since he is the household head and the one who has given her the freedom to make decisions independently.

Women also explained that age and position in the household are important factors in the level of agency they possess. For example, women on step five of the ladder (i.e., power and freedom) were said to be "*mature people who can make decisions on their own*" or widows, while those on step one (i.e., no power or freedom) were likely elderly women living with, and depending on, their children. One woman explained from her own experience that her decision-making authority had increased when she got married and had children since she now has to make decisions for her children and tells them where to work and what to do on the farm.

In contrast to women, male participants indicated a small decrease in men's power and freedom in recent years. Their reasons mirrored those raised by women. In the past, men had been in charge of all household decisions without question but that, as women and children had become more educated, men now acknowledge they have valuable knowledge and ideas on how to improve and develop the family and will consult their wives and family members. Nevertheless, men still regarded themselves as having more decision-making authority than their wives.

Asked whether the opportunities in agriculture for men and women had changed over the past five years, two reoccurring themes emerged from the FGDs and interviews. On the one hand, opportunities had proliferated due to increased agricultural training and better knowledge of new farming practices such as the application of pesticides, use of soil and water conservation techniques and poultry keeping. On the other, farming conditions were said to have worsened due to poor and unreliable rainfall. As one women interviewee explained, "*There is an improvement. We have been trained in better methods of farming and have good varieties of seed favourable to this area, but the rains fail us*".

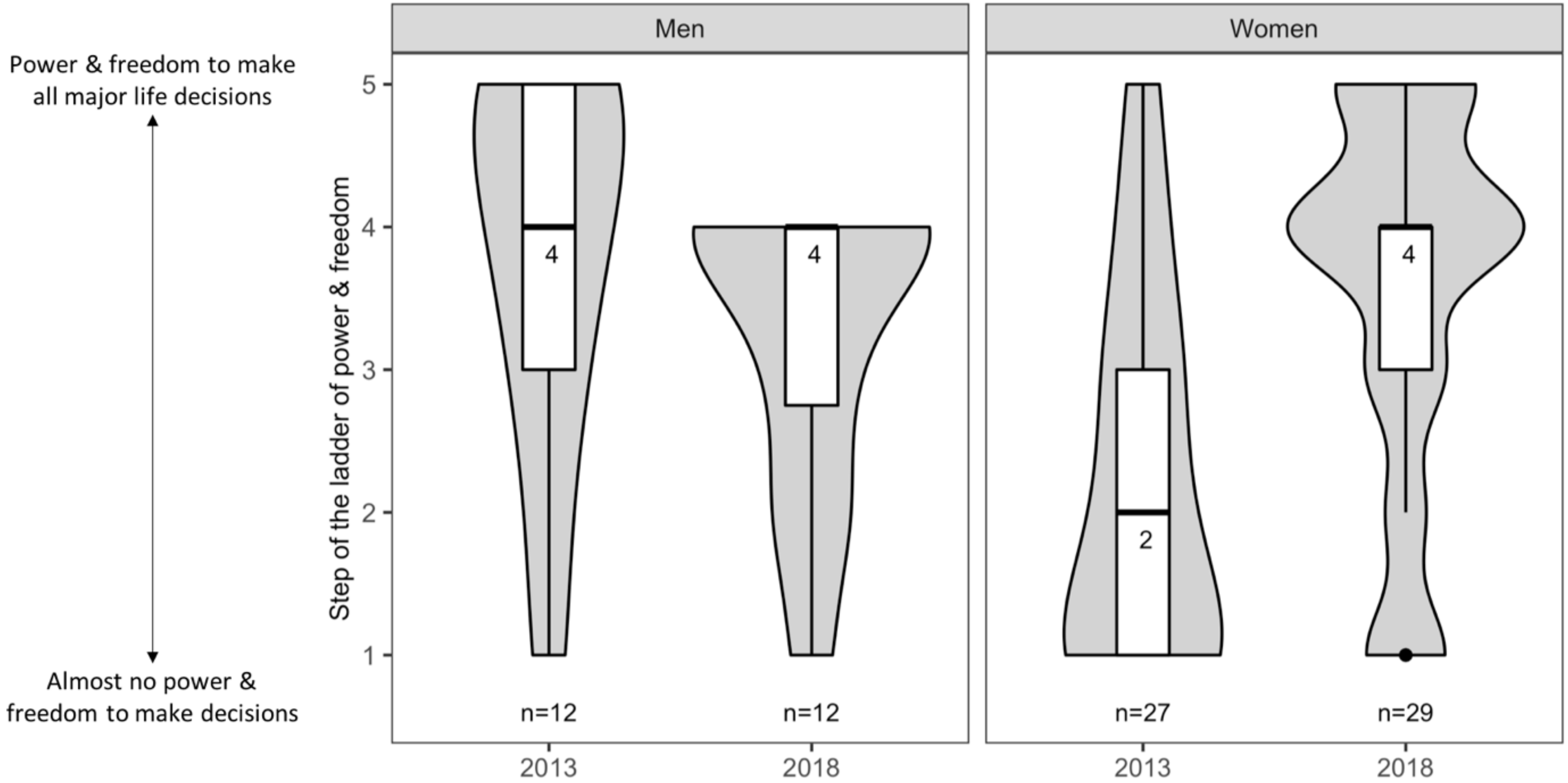

Figure 5.3 Men's and women's votes from the Ladder of Power and Freedom exercise during focus group discussions. Median scores shown. Women indicated a substantial increase in their level of agency over the past five years, while men indicated a slight decline.

There was a consensus that women had benefited the most from increased opportunities in agriculture, since they are the ones mainly involved in farming and who attend training events, while men look for off-farm income. Women interviewees saw farming as a way to earn income and provide food for their families, and their plans for the future included gaining access to water for commercial production of vegetables, poultry farming and starting small shops to sell their produce. Nevertheless, several interviewees indicated that women's involvement and interest in farming is born out of necessity rather than choice. As one woman explained, mainly women are interested in farming, "*because men move and leave the women and children behind. These women have no option but to work on their farms*". Another stated, "*[women] are the ones burdened with raising their children compared to their husbands. The women provide the food, clothes and are more concerned compared to the men. The men leave early and come back late they don't even know when the children are hungry".* Such accounts imply that, while women's opportunities in agriculture are thought to be increasing, norms designating them as carers of the household and as vulnerable in urban settings, constrain their ability to explore opportunities outside of farming.

3.3 Aspirations survey: men's and women's envisioned futures

Although we did not ask aspiration survey respondents (storytellers) directly whether their spouses had migrated, 23% of women mentioned that their husbands were temporarily absent or lived and worked away. A further 5% were divorcees and 10% were widows, likely explaining the high percentage of women storytellers self-identifying as the household head (27%). Most men and women perceived their stories as positive (98%), however, women saw their world filled with fewer opportunities than men had and, although still high (median of 74%), were less confident in achieving their goals (Table 5.3). Women also envisioned spending more of their time farming than men, yet both men and women indicated to a similar degree that they care about improving their farming, perhaps reflecting men's intentions to return to farming when they retire.

Table 5.3 Summary statistics for self-assessment dyads.

	N	Mean	Median	Std. Dev.	Min	Max
Level of confidence in achieving goals (0-100)						
Men	49	79.82*	81.00	11.68	52.00	95.00
Women	85	73.46*	74.00	14.09	33.00	97.00
Level of perceived opportunities in life (0-100)						
Men	50	57.70*	65.00	21.54	16.00	88.00
Women	86	49.37*	59.00	22.24	5.00	87.00
Share of time spent farming (0-100)						
Men	48	54.33*	67.00	29.29	4.00	92.00
Women	83	65.72*	75.00	23.81	0.00	92.00
Degree to which people care about improving their farming (0-100)						
Men	45	73.84	75.00	14.23	19.00	95.00
Women	81	71.64	74.00	13.44	13.00	89.00

* $p<0.05$ Wilcoxon rank-sum test

There were distinct trends in aspirational focus with age and gender (Figure 5.4). None of the men or women under 25 aspired to farm. Instead, their aspirations focused on their education, securing employment, starting their own businesses and rescuing their families from poverty. Men's and women's aspirations then diverged and re-converged with age. While most women aged 25-35 aspired to invest in agriculture, men of the same age aspired to own businesses, find employment and saw farming as a largely secondary activity. Conversely, despite many women in this age group reporting that in addition to farming they currently look for casual work or have small businesses, they spoke of becoming "*established*" and "*large-scale*" farmers, with farming seen as a way of earning income. As one woman explained, "*I have 40 mango trees now which I want by 2028 to increase to 200 trees so I may be able to sell many bags of fruits and be able to give me income. I also plant crops like maize, vegetables and beans. I also have ten goats which I want to increase and sell to gain profits*".

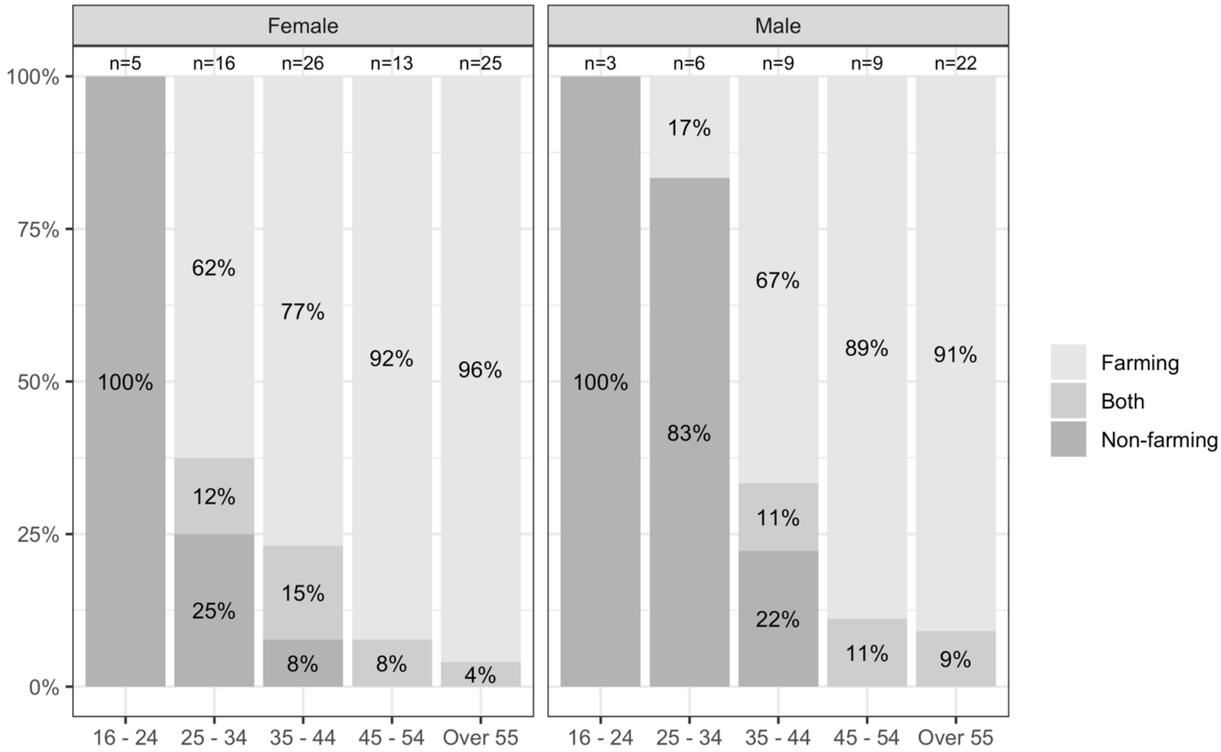

Figure 5.4 Aspirations of men and women storytellers across age groups, categorised by whether they mentioned non-farming or farming related aspirations in their stories or both. Farming-focus aspirations were more common among older age groups and among women compared to men for ages 25 to 44 years.

There was an increased focus on agricultural activities for men and women aged 35-44 years. Nevertheless, it was again women rather than men who emphasised commercialising their agricultural activities. One woman even aspired to own a tractor and to become a "*full-time farmer*", despite later indicating that she currently runs a small boutique in her local market: *"I want to keep a lot of poultry and ensure I am a full-time farmer. I want to also take part in large-scale crop farming using tractors by planning to buy my own tractor".* Such findings challenge the notion that rural women are primarily interested in farming for home consumption.

Among older cohorts, both men's and women's aspirations coalesced towards agriculture with men over 45 years often looking to retire from their off-farm occupations and return to farming. As one man aged 45-54 explained, "*in the next ten years I want to buy tanks and store rain water and start irrigation. I have already bought two that hold 10,000 litres and will add more soon. Currently I am a casual worker in Nairobi about to retire".* Furthermore, unlike younger cohorts, it was primarily men within the over 55 age group who emphasised commercial production and wanting to sell their farm produce to "*big markets*", perhaps reflecting their return to farming following retirement. As one man illustrated, *"since I am a retired teacher I want to be a farmer. I would like to plant mango trees and keep poultry. I want to take farming more seriously than before because right now I have the time".*

While storytellers' farming aspirations were diverse, the specific activities mentioned by men and women did not significantly differ. Common activities mentioned by both men and women included digging farm ponds or buying water tanks, acquiring more livestock or land, starting dairy farming or poultry farming and growing horticultural crops. There was also a strong focus on planting fruit trees, especially mango. Unlike younger cohorts, men and women over 55 planned to move into less labour-intensive activities such as poultry and fruit trees given that crop farming would likely become difficult due to old age. In contrast to farming activities, non-farming occupations and aspirations held by men and women were often stereotypically associated with their gender. For example, women's non-agricultural aspirations often included owning a hair salon or clothing business, or starting a kiosk or grocery store in the local market, while men spoke of owning their own transportation businesses, working in construction, becoming a mechanic or building rental apartments.

Storytellers also mentioned non-occupational aspirations. For example, two of the women under 25 wished to rescue their families from poverty, while one young man who aspired to be a politician stated that he wanted to "*improve the lives of his people*". In older cohorts, non-occupational aspirations focused heavily on educating children, specifically to tertiary level, so that they could "*secure good jobs*", "*get employed*" and earn an income. 43% of men and women over 25 mentioned wanting to educate their children and investing in farming was often seen as a way of earning money in order to do so, especially by women. Several men and women over 55 planned to depend on their children in their old age. As one woman explained, "*I have no plans. I will just continue with small-scale farming as I have always done. My children are grown up, so when they stabilise I expect them to take care of me".*

4. Discussion

Four key points emerge from our exploratory study. First, women are likely to be important catalysts of agricultural innovation and investment amid the increasing outmigration of men and feminisation of farm management. Secondly, if rural aspirations are to be used to target development efforts more effectively, researchers will need to consider the aspirations of multiple household members and how they interrelate and are mediated at the household level. Third, attention should be paid to gendered and inter-generational roles and relations within the household and, fourthly, to how men's and women's opportunity spaces change throughout life. In the following section, we discuss these four points and their implications for future aspirations research.

4.1 Women's increasing agency and opportunities in agriculture

A common narrative within agricultural development is that women, given their responsibility for feeding the family, are primarily interested in innovations related to food production for home consumption, whereas men are more concerned with those aimed at optimizing agricultural income (Doss, 2001; Fisher and Carr, 2015; Shibata et al., 2020). Whilst this narrative is not unfounded, we contend that, at least in the context of eastern Kenya and increasing male outmigration, such notions may require re-examining.

We found that, while middle-aged men often aspired to invest in off-farm income sources, women largely aspired to invest in and commercialise their agricultural activities and saw farming as an opportunity, not only to provide food for their families, but to earn an income. Even women who reported having off-farm income sources often aspired to expand their current farming activities to increase earnings. These findings are in contrast to those of Rietveld et al. (2020) and Elias et al. (2018) who found that, in several sub-Saharan contexts, women's agricultural aspirations are constrained by social norms designating farming and, in particular, commercial agriculture, as an occupation better suited to men. Unlike the majority of women in our study, none of the young Ugandan women interviewed by Rietveld et al. (2020) aspired to be farmers, and when farming was considered as part of their future livelihood, their interest was generally limited to farming for subsistence or as a means of diversification. This is not to say that in our study women's interest in farming is not initially shaped by norms and attitudes that constrain their off-farm opportunity space and limit their options to primarily farming-related activities (Van den Broeck and Kilic, 2019). For example, similarly to Ifejika Speranza (2006), we found evidence for norms and attitudes discouraging married women from engaging in migratory employment.

Furthermore, although off-farm income activities mentioned by storytellers were often stereotypically associated with their gender, the differences in the farming-related aspirations mentioned by men and women were limited. However, it is worth noting that the opening question to our aspirations survey was purposefully neutral and without reference to farming or non-farming activities so as to elicit an unrestricted response across all possible livelihood strategies. Consequently, storytellers often referred to "farming", rather than specifying the specific types of agricultural activities they wished to pursue. Further questioning around the types of farming people aspired to invest in may therefore have revealed greater variation between men's and women's aspirations within agricultural strategies.

The feminised focus on agricultural investment revealed by our study likely reflects women's changing agricultural opportunity space amid the increasing off-farm employment and outmigration of men. While the temporary migration of adult men has long been a recurring trend within our study area (Tiffen et al., 1994), the numbers of those leaving for cities in search of work was reported to have increased in recent years, and almost a quarter of women storytellers reported that their husbands live and work away. As a result, women are the ones largely attending agricultural training events, gaining knowledge of new technologies and taking advantage of new opportunities in agriculture. Furthermore, women's participation in, and agency over, household and farming decisions is thought to have increased substantially in recent years due, at least in part, to the absence of their male household members. These findings are similar to other studies, including those conducted in Kenya, indicating that women's increased agricultural training can increase their confidence and involvement in farming decisions (Bullock and Tegbaru, 2019; Nyasimi and Huyer, 2017), and that women with absent husbands may gain greater personal autonomy and power over household decisions (Yabiku et al., 2010).

Rietveld et al. (2020) suggest women's disinterest in commercial farming stems from the likelihood that their husbands will claim any resulting revenue. Likewise, in Meru County, Kenya, Dolan (2001) document that rural women are often reluctant to take on certain commercial crops since it increases their workload, but not their controlled income. Hence, the accounts of women in this study which frame farming as a potential income generating opportunity may be indicative of a dynamic whereby, with men away from home (i.e., engaged in migratory work), women gain more control over the financial rewards of farming and, as a result, are increasingly interested in pursuing commercial agricultural activities.

Several pertinent questions and lines of enquiry emerge from the above findings. One such question is whether women's increased agency reflects lasting changes in family relations and gender-related norms, or whether these gains are simply a practicality in the physical absence of men. Encouragingly, Yabiku et al. (2010) found that in southern Mozambique, increases in women's autonomy persisted even after their male relatives returned. In our study, however, male storytellers spoke of returning to farming once they retire, raising questions regarding women's security in their role as farm managers. As illustrated by Dolan (2001) with the commercialisation of French bean production in Meru, men may also choose to appropriate women's agricultural enterprises once they are commercialised.

Another important question is whether people's aspirations are, in fact, attainable. While phrases such as '*I want to be a large-scale farmer*' indicate that women are certainly interested in farming, their stories alone do not provide detail as to the scale of this envisioned production nor if these goals are realisable. Given small farm sizes and marginal farming conditions, the financial returns to women's investments in farming may well be limited. In light of this, we propose that combining narrative-based approaches, such as SenseMaker®, with more conventional socio-economic household surveys could prove more effective in informing the design of development efforts and identifying the barriers people face in attaining their aspired futures.

4.2 Recognising intrahousehold heterogeneity of aspirations

Both Verkaart et al. (2018) and Mausch et al. (2018) argue that development projects could benefit from considering inter-household variation in aspirations and targeting households who truly aspire to farm. Based on our findings, we further propose that rural development projects should identify those *within* the household who aspire to farm. Our study suggests that, at least in the drylands of eastern Kenya, it is often the women within rural households who are likely to be a key target group, given their interest and enthusiasm for farming and their increasing agency over management decisions. These conclusions, however, reveal an apparent shortcoming of current rural aspirations research – a lack of consideration of the *intra*-household heterogeneity of aspirations and that asking for the aspirations of only one household member is likely to provide a biased picture of a household's desired livelihood trajectory.

Research on rural livelihood strategies tends to focus on the household as the unit of analysis and usually relies on surveys conducted with one household member, often the household head. However, in contexts where adult men frequently engage in off-farm income-generating activities, studies that ask only for the aspirations of the household head risk concluding that rural households do not aspire to grow the agricultural aspects of their income portfolios but instead wish to focus on off-farm sources of income. If researchers are to utilise aspirations to target rural households more efficiently, it will be critical to assess the aspirations of multiple household members and how these interrelate and are mediated at the household level.

For instance, in their assessment of aspirations among rural Kenyan households, Verkaart et al. (2018) evaluated livelihood strategies at the household level but subsequently only asked the survey respondent (presumably, often a male household head) what income-generating activities they personally aspired to invest in. Based on their analysis, they conclude that a sizable proportion of households aspire to invest in their non-farm income sources rather than in farming. From their sample of 624 households, 64% of respondents wanted to invest in farming, 41% in non-farming activities and 9% in both farming and non-farming activities. Our research suggests, they may well have concluded otherwise had they considered the aspirations of multiple household members and, in particular, their wives. We therefore propose that researchers studying rural aspirations and livelihood dynamics could benefit from taking an approach that recognises that within a household, there may be those who wish to remain and engage in farming even when other members look to step out.

4.3 Changing opportunities, interests and capacities throughout life

In line with Sumberg et al. (2012), our findings suggest that specific events throughout life, such as finishing school; inheriting land; getting married; and having children, work to reshape men's and women's opportunity spaces in distinct ways, opening up or constraining their interest and capacity to engage in farming or other activities. Specifically, our study, similar to Rietveld et al. (2020), highlights the interrelated role that marriage and access to land play in shaping men's and women's opportunities.

For both male and female storytellers, we found an increased focus on farming among older age groups. Supported by a general trend towards larger farm size with age (Table 5.1), this likely reflects young men's and women's limited access to and control over land, and thus their current lack of opportunities in farming. In our study area, young men tend to inherit land once they are married or must wait until they have saved up sufficient capital to purchase land of their own, while women generally gain access to land through their husbands following marriage (Musangi, 2017). Moreover, young men's and women's access to land is likely to be further constrained by the successive subdivision of land through inheritance (Jayne et al., 2014).

For men, an increased focus on farming with age is also likely to reflect a return to farming in their retirement. For women, marital status seems to play an additional role in shaping their engagement in farming. In Kenya, getting married marks a person's transition into adulthood and, for many women, a point at which certain options in life, such as education and formal employment, foreclose (Ikamari, 2005). For instance, norms discouraging women's engagement in migratory labour appear to be less binding for younger, unmarried women in Makueni County. Once married, however, women are expected to remain on-farm and take care of the home and children.

While the above findings provide initial insights into the dynamic nature of aspirations, it is important to note that our collected narratives provide only a snapshot of people's aspirations and are likely biased towards those who remain living in rural areas, as indicated by the low numbers of youth and men in our sample. It is therefore unclear to what extent young men and women who aspire to move out of farming do so and are therefore not captured in our sample, and whether the trend in men's and women's stories towards farming-related aspirations with age reflects a socio-cultural shift in aspirations away from farming. Answering such questions, however, will require further in-depth enquiry, for instance using longitudinal studies that track people's aspirations over time and how aspirations play out throughout life and with men's and women's changing circumstances and social identities.

4.4 Understanding intrahousehold roles and relations

Our research also highlights the need to consider how individual livelihood strategies and aspirations interrelate and are mediated at the household level. While individuals within the same household may differ in their preferences and priorities, household members often own and manage resources collectively and make decisions together to achieve mutually beneficial outcomes (Doss and Meinzen-Dick, 2015; Doss and Quisumbing, 2020). In our study, men's and women's diverging and converging aspirations with age likely reflect gender- and age-dependent divisions of labour and familial responsibilities, and even a negotiated household strategy. For example, there is a sense that children are expected to focus on their education so that they can secure employment and provide their families with long-term financial security. For married women, responsibilities shift towards caring for the household, raising children and managing the farm, while men continue to engage in off-farm income activities, either locally or further afield, until their retirement. Furthermore, migration was seen as part of a household strategy, with a migrant's decision to leave often reported to have been discussed and decided on as a household.

Given women's stated agency and increased involvement in household decisions in recent years, one could speculate that these gender-differentiated roles and responsibilities reflect a negotiated, and even preferred, position for women. As argued by Archambault (2010), while the term 'left-behind' designates rural women as passive actors in their husband's migration and residency decisions, rural women may also choose to remain out of their own volition. In their study on rural women's autonomy amid male outmigration in north-eastern Tanzania, Archambault (2010) found that women may chose to remain given increased autonomy over their labour and work schedule. Similarly, in central Kenya, Nelson (1992), report that women may remain for a variety of reasons, including increased personal and economic autonomy in the absence of their husbands, a feeling of being appreciated by their families and seeing farming as their way of contributing to their household's welfare, as well as an aversion to urban life and the prospect of moving to the city, only to become a housewife.

Nevertheless, several women interviewees in our study framed their role in farming in a more negative light, even stating that '*women have no option but to work on their farms*', and although women have experienced increased agency in recent years, it is evident that asymmetries in decision-making authority persist, with men still seen as the household head and final decision-maker. It is also worth noting that the women participating in our FGDs and interviews are those engaged in a land restoration project and unlikely to represent the heterogeneity of women within the community. For instance, the majority of women involved in the project are aged between 35 and 54, married and have access to land. Compared to younger women, especially those with young children, these women are likely better able to negotiate greater access to land, influence household decisions and have the time and mobility to attend project training events (Rietveld, 2017). Although our Ladder of Power exercise focused on changes at the community level, its results likely hide considerable variation in the socially differentiated experiences of women and care should be taken not to overstate women's increased capacity to exercise agency. An important avenue for future aspirations research is therefore to explore to what extent aspirations are negotiated among household members and what this means in terms of different groups of women's actualized power to decide their own futures and that of their households.

5. Conclusions

In this study, we contribute to growing evidence that multiple social dimensions, including gender, age and household position, intersect to shape an individual's opportunity space and aspirations for the future. In the absence of men and presence of norms restricting women's movement out of rural life, women in Makueni are becoming increasingly engaged in farming both in terms of labour and management decisions. At the same time, women's participation in agricultural training has led to increased recognition of their capabilities as farmers and in their own confidence in managing the family farming enterprise. Challenging the notion that women are primarily interested in subsistence farming, women's aspirational narratives focused on intensifying and commercialising their farm activities, likely reflecting this changing opportunity space in agriculture and their new realities as farm managers.

Our findings also highlight that considering aspirations at only the household level ignores how individuals often contribute to and control different aspects of a household's livelihood portfolio and may aspire to invest their time and resources in distinct ways. Further, our study underscores how analysing aspirations at only the individual level overlooks the relations between household members and that aspirations are likely shaped by the views and actions of others. If development efforts are to utilise rural aspirations to target agricultural innovations more effectively, future research must move beyond studying the desired futures of individuals in isolation from their wider household and move towards a more collective model that recognises the intrahousehold heterogeneity of aspirations and the dynamic nature of the gender and age-related roles and relations that underpin them.

Chapter 6: Synthesis and conclusions

The research presented in this thesis was conducted within the context of a large-scale land restoration project (World Agroforestry, 2020). From the outset, my motivation was to produce actionable insights for restoration practice and projects employing a research in development (RinD) approach, including the use of planned comparisons. While my work centred on restoration activities within a single scaling domain (i.e., three counties in eastern Kenya) and the use of planting basins for maize production, the research presented offers several insights that contribute to current debates and emerging areas of enquiry in agricultural development, as well as more practical recommendations for RinD approaches (see Appendix 8 for stakeholder summaries). In the following sections, I summarise the main findings from each chapter and reflect on their implications for development-focused agricultural research and the future of smallholder agriculture in eastern Kenya. Finally, I discuss the limitations of my study and how the methods and approaches used in this thesis could be integrated to provide a more systemic evaluation of agricultural innovations.

1. Summary and overview

The overarching aim of this thesis was to assess the impact of restorative farming practices on the livelihoods of smallholder farm households, so as to improve the specificity of recommendations and scaling of restoration efforts. Its four main chapters reflect the sequential evolution of my research over the course of the past four years. While my focus at the inception of this project was solely on the development of farm-scale models, it was through working with farmers to conduct on-farm trials and hearing women's stories of their increasing role as farm managers that the importance of gender relations within households became increasingly evident. This led me to broaden my research scope and take a deep dive into the intrahousehold dynamics surrounding the uptake of restorative farming practices and women's shifting agricultural opportunities and aspirations amid male outmigration. In turn, these developments led to two main streams of enquiry: the first, focusing on quantifying the impact of planting basins on the livelihoods of smallholder farm households (Chapters 2 and 3), and the second, on examining how intrahousehold gender relations shape the uptake of restorative farming practices and men's and women's aspirations in and out of agriculture (Chapters 4 and 5).

In Chapters 2 and 3, we employed various methods for assessing the performance of planting basins and their contribution to transformational change in household livelihood outcomes in terms of maize self-sufficiency and income. In Chapter 2, the use of simple calculations and descriptive analyses enabled us to move beyond average yield effects and assess variation in yield response and economic impacts of planting basins at the household level. In Chapter 3, we developed a farm-scale model to extend the analyses conducted in Chapter 2 and explore the ex-ante impact and viability of planting basins for two households with contrasting resource endowment.

Chapters 4 and 5 took a more qualitative and inductive approach and focused on the gender dimensions of farmland restoration and agricultural investment. In Chapter 4, we combined survey data on decision-making and labour participation over the planned comparisons with interviews and focus group discussions to explore how gender roles and relations influence the uptake and use of planting basins and tree planting. In Chapter 5, we explored men's and women's livelihood aspirations – a topic that has garnered little attention despite its potential for guiding rural development. Here, we analysed aspirational narratives from men and women collected using a novel, narrative-based survey tool and used focus group discussions and interviews focused on migration to explore the changing roles and aspirations of rural women amidst intensifying migration flows.

Four general insights for implementing development-focused agricultural research can be distilled from the findings of these core research chapters. First, is the need for researchers to move beyond a fixation on differences in mean yield and attempt to understand variability in innovation performance. Second, is the need to translate field scale metrics into farm scale metrics that are meaningful to households and their members. Third, is the need for intrahousehold approaches to the evaluation of innovations that consider gender roles, responsibilities and preferences within households and livelihood strategies. Last, is the need to consider the broader social and economic trends within which restoration and agricultural development is occurring, including diversification of rural livelihoods and the feminisation of agriculture.

1.1 Move beyond average yield effects and attempt to understand variation in innovation performance

In Chapter 2 we revealed strong variation in yield response to planting basins across farms. This variability in treatment response highlighted the considerable risk posed to farmers when planting basins are promoted and adopted as a generalised recommendation. Findings from this Chapter therefore contribute to the growing recognition that average yield effects are of little value when it comes to estimating the benefits from innovations for individual farmers, and that measures and assessments of variability are needed (Coe et al., 2016; Vanlauwe et al., 2019). Similar to recent studies (Franke et al., 2019; Ronner, 2018; Vanlauwe et al., 2019; Vugt et al., 2018), we found that presenting yield response and economic metrics (gross margin, returns to labour, personal daily income etc.) as cumulative frequency curves particularly useful for demonstrating variability in performance and potential risk of adoption.

As proposed by Coe and colleagues, understanding the causes of this variation in innovation performance could lead to better tailored agricultural recommendations with more reliable outcomes for farmers (Coe et al., 2016; Vanlauwe et al., 2019). In Chapter 2, we found in-season rainfall, altitude, and the application of farmyard manure to be important factors associated with yield response to planting basins. Yet, although these findings enabled us to make several general recommendations for the use of planting basins, the vast majority of explained variation was attributed to project site (i.e., sub-county). Unfortunately, knowing that basins work well in some sites and not others provides little insight into what might happen in other locations. Our study was therefore limited in its ability to predict innovation performance and formulate farmer-specific recommendations on the use of planting basins.

As noted by others seeking to understand variation in innovation performance, fully understanding variability is a challenging endeavour in the face of confounded variables, diverse management practices and noisy data (Franke et al., 2019; Ronner, 2018; Vugt et al., 2018). This thesis illustrates that understanding the causes of variation in yield response requires collection of data on relevant factors, including farmers' adaptations of practices. Our monitoring surveys overlooked several key agronomic practices such as plant population and biophysical factors such as soil type and slope (Mupangwa et al., 2008; Nganga et al., 2019; Nyagumbo et al., 2016). They also failed to capture the large variation in the implementation and management of planting basins amongst farmers. If we, as researchers, are to better understand variability in innovation performance, we must accept that farmers modify practices and seek to adequately capture and document farmer adaptations in our evaluations.

Chapter 3 further revealed the variable nature of innovation performance but, in this case, in response to climate variability. Developing a farm-scale model to extend results from Chapter 2 allowed us to assess the implications of using planting basins beyond just a few seasons and under varying rainfall conditions. We found that using nitrogen fertilizer without basins provided large yield and economic benefits in years with exceptionally high rainfall but presented substantial losses in those with poor rainfall. In contrast, planting basin scenarios provided modest gains in most years and showed greater inter-annual yield stability. Evaluations that consider innovation performance under varying rainfall conditions are increasingly pertinent in the face of climate change, with increased rainfall variability and extreme weather events predicted for East Africa (Rowell et al., 2015; Wainwright et al., 2021). Dynamic simulation models such as those presented in Chapter 3 could be a powerful tool for exploring the impact of innovations under future climate change scenarios. Our model outputs also indicate the importance of when and under what conditions innovations are tested and opportunities to complement basins with interventions such as timely and accurate weather forecasts, and the value of such models in demonstrating potential variability and risk to farmers with the uptake of new technologies.

1.2 Translate field scale metrics into farm scale metrics that are meaningful to households and their members

This thesis contributes to growing recognition of the need to evaluate innovations in a much broader sense than usually done within agricultural research (Sinclair, 2017; van Ginkel et al., 2013). In Chapters 2 and 3, we attempted to build upon the work of Coe and colleagues (Coe et al., 2016; Vanlauwe et al., 2019), by not only examining variability in yield response, but by taking our analyses one step further and translating plot level metrics into farm level metrics. These included metrics that are likely to be more meaningful for farmers and their households, such as the number of additional days of grain provision for their family members and stover for their livestock, increases in personal daily income and changes in resource use efficiencies.

Compared to plot level metrics, the analyses presented in Chapter 2 and 3 provided a more realistic picture of the extent to which planting basins can lead to meaningful changes in livelihood outcomes, and that even relatively simple back-of-the-envelope calculations can be a useful first step towards more farmer-relevant assessments. Both Chapters indicated that, although unlikely to lead to transformational change in terms of per capita income, integrating planting basins into current farming systems can provide a critical safety net in terms of household food security and in the face of climate variability. Traditional performance metrics such as yield per hectare and intensity of adoption are likely to overlook the less direct role innovations may play within livelihood systems and their resilience. Shibata et al. (2020) for example, deemed households as adopters of conservation agriculture only when over 50% of their cultivated area was cultivated using planting basins. Yet, as indicated by our study, even small areas of basins may be playing an important function within the livelihood system, buffering households against climatic shocks and yield failures.

1.3 Take an intra-household approach and assess the impact of innovations on men's and women's time and agency

Many adoption studies still frame technological change in terms of the economic rationality of individual choices, but there is growing recognition that innovation processes are shaped by social relations and negotiations amongst actors, including those living within the same household (Badstue et al., 2020; Farnworth et al., 2020; Glover et al., 2019). Agricultural development projects commonly target farmers through training workshops, farmer meetings and field visits. These dissemination approaches largely rest on the assumption that once an individual gains knowledge on how to implement a promising new farming practice, they will return home and try it out for themselves. Yet, similar to other studies across East Africa (Shibata et al., 2020; Theis et al., 2018), Chapter 4 revealed that at least within married households, the uptake of restorative farming practices is generally not a unitary decision made by individuals acting alone, but involves some form of consultation between husband and wife. Furthermore, we found that these spousal relations can present a potential barrier to the uptake of restorative farming practices, particularly for women. In this way, the household can be seen as a filter, mediated by gender relations, through which uptake decisions must pass before a new practice is implemented.

Assumptions over who is involved in uptake decisions can have important implications for the dissemination of agricultural interventions. Restoration projects that target farmers without considering the wider household and how uptake decisions are made are likely to miss opportunities for greater adoption of on-farm restorative practices. Land restoration projects therefore need to understand, not only who is involved in uptake decisions, but also how they are made and the extent to which individuals have agency and voice in a decision. Similar to Acosta et al. (2019), we found considerable variation in understandings of what it means to take part in a decision. For example, consultation was seen by men as a way of ensuring their wives felt included in a decision and, despite having a limited voice, were more likely to contribute their labour. Such findings highlight the complexities of intrahousehold decisions and call into question what it means to have taken a decision jointly. As argued by Acosta et al. (2019) and illustrated by Chapter 4 and other studies (e.g., Ambler et al., 2019; Bernard et al., 2020), quantitative surveys alone are unlikely to adequately capture the complexities of intrahousehold decision-making and need to be complemented with in-depth qualitative investigation.

In Chapter 4 we also found that on-farm restoration practices can alter when associated farming activities occur, how long they take and who is involved. In line with Baudron et al. (2007) and Nyanga et al. (2012), our findings suggest a shift in the burden of land preparation from men to women with the uptake of basins. Yet, despite this potential increase in labour, women perceived the of digging planting basins to be worthwhile. This thesis thus highlights the importance of not only understanding how restoration efforts influence the men's and women's workloads, but also how farmers perceive and value their time and benefits from these practices (Njuki et al., 2014; Theis et al., 2018). While quantitative approaches such as those presented in Chapter 2 show the time spent digging basins may not be worthwhile for many, farmers, especially women, may value costs and benefits differently and perceive that the benefits outweigh the labour requirement. Restoration initiatives should therefore conduct gender analysis of innovations not only during their design but also following their uptake and include the views and perceptions of project beneficiaries when assessing the costs and benefits from restoration activities.

1.4 Consider the broader social and economic context within which restoration and agricultural development is to occur

Conducted against a backdrop of increasing rural-urban migration and feminisation of agriculture, this thesis emphasises the need to link the micro- and macro- scales and place agricultural research in the context of the wider demographic and structural changes occurring across sub-Saharan Africa. These include: i) increasing diversification of rural livelihoods and importance of non-farm income sources (Barrett et al., 2001; Haggblade et al., 2010; Harris and Orr, 2014); ii) increasing mobility and de-localisation of livelihoods as people – primarily younger men – move to urban areas, in turn, changing both gender and age structures of rural populations (Mercandalli et al., 2020); and iii) decreasing farm sizes and land-to-person ratios as a result of increasing rural population and land division through inheritance (Jayne et al., 2010; Rigg, 2006).

As demonstrated in Chapters 4 and 5, consideration of the intrahousehold relations that underpin men's and women's livelihood strategies, and aspirations are increasingly pertinent in the face of such 'mega trends'. Where local labour markets are inadequate and farms insufficient in size and quality to ensure a reliable livelihood, household members seek to diversify their income streams through migratory wage labour, leaving their homesteads for extended periods of time (Mercandalli et al., 2020). As we see in Chapters 4 and 5, resultant changes in household structures can lead to redistribution and redefinition of household responsibilities, with women assuming the role of primary farmer (Yabiku et al., 2010). This reconfiguration of responsibilities can increase both the physical and emotional burden on women, but equally give women greater agency over household and farming decisions in ways that allow them to further their wants and needs (Saha et al., 2018; Slavchevska et al., 2016; Yabiku et al., 2010).

In line with a growing literature (Chant and Radcliffe, 1992; Saha et al., 2018; Yabiku et al., 2010), our findings show that women with migrant husbands often have greater agency over farming decisions than women with resident husbands. Nevertheless, given that on-farm efforts to restore degraded lands are often labour-intensive, their promotion in regions experiencing increasing male outmigration risks placing the burden of restoration disproportionally on women. Yet, despite its implications for land restoration efforts, as far as we are aware, the impact of increasing migration on the capacity of rural households to restore degraded lands remains largely unexamined and a pressing issue for future research.

In Chapter 5, women's aspirational narratives focused on intensifying and commercialising their farm activities, likely reflecting their changing opportunity space in agriculture and new realities as farm managers in the absence of their male relations. At the same time, we found evidence that women's participation in agricultural training has led to increased recognition of their capabilities as farmers and in their own confidence in managing the family farming enterprise. Nevertheless, in the face of small farm size and limited returns from farming an important question is whether women's aspirations to become "large-scale" farmers are, in fact, attainable (Harris and Orr, 2014).

2. The future of smallholder farming

Despite increasing rural-urban migration and the variable returns from rain-fed agriculture, smallholder farming will likely continue to play an important role in the livelihoods of those living in the drylands of eastern Kenya. In Chapter 3, our model indicated that maize production using planting basins was, on average, unable to provide returns to labour comparable to off-farm employment and, in some years, returns were negative. Yet, in high rainfall years maize production even without the use planting basins provided labour returns far greater than skilled off-farm employment. This suggests that, in some years, investing in crop production may still be worthwhile, especially if non-farm income opportunities are limited and unreliable.

Migration and farming are not necessarily mutually exclusive livelihood strategies; both can play an important role in diversifying household income streams and increasing livelihood resilience in an uncertain world. As noted in Chapters 4 and 5 and Verkaart et al. (2018), even when households invest in non-farming activities such as migratory wage labour, they often choose to keep one foot in farming, retaining land as a safety-net in the face of job insecurity, for their retirement, or because they culturally identify as farmers. Given that smallholder agriculture will likely remain an important part of rural livelihood portfolios for the foreseeable future, effective policies are needed to support smallholder producers and increase both the profitability and ecological sustainability of small-scale farming systems. Such policies include: i) increasing profitability and incentivising action against degradation; ii) improving access to extension services, especially for rural women, and lastly, iii) policies that sit outside of agriculture, and which aim to strengthen rural-urban connections.

2.1 Improving profitability and incentivising action

One of the driving hypotheses behind this thesis was that land restoration options can improve food security and reduce poverty for rural people in the drylands of Kenya but need to be locally adapted to fine scale variation in livelihood context to do so. Findings from this thesis suggest that although restorative farming practices – in this case planting basins – may help buffer against climate variability and provide a safety net in terms of food security in times of drought, the adoption of a single practice alone is unlikely to transform rural livelihoods and lift households out of poverty.

To improve the transformative potential of restorative farming practices, they not only likely need to be adapted to local farming contexts but combined and complemented with additional innovations, both on and off the farm. In the case of planting basins, this could include finding ways to mechanise their construction and reduce their labour requirement; using basins to grow higher value crops other than maize; integration with rain water harvesting and supplementary irrigation; providing timely and accurate weather forecasts; incentivising the use of restorative farming practices through subsidies or payments for ecosystem services, and using improved agronomic practices, such as diversifying crop rotations, intercropping, judicious use of inorganic fertilizers, and increased application of organic inputs, to help increase and maintain soil organic carbon and fertility.

2.3 Investing in rural extension services

In addition to being labour intensive, restoration practices are often knowledge intensive (e.g., soil and water structure construction, tree planting practices, manure management and storage). Given that agricultural extension is a key driver of agricultural innovation and changing farming practices, improving the access of farmers, especially women, to training and information on the use and management of restoration options would likely improve uptake and the efficacy of such practices. Nevertheless, whether county governments currently have the capacity to provide improved extension services is unclear.

In Kenya, the devolution of agricultural services from the national government to the administrative counties was intended to lead to better rural service delivery and enhanced agricultural productivity, the realisation of these goals has been variable and local governments often lack the capacity and resources needed to deliver public services effectively (World Bank, 2018). Potential ways to overcome such constraints include building collaborative partnerships between local government, research institutions, NGOs, and other development actors to scale up land restoration efforts, or through innovative and cost-effective extension models such as farmer-to-farmer learning (Franzel et al., 2019; Kiptot and Franzel., 2019) and using information and communications technologies, such as mobile phone and app-based platforms to disseminate knowledge (FAO, 2017).

2.4 Supporting rural-urban connections

Smallholder farmers might also benefit from non-agricultural focused policies. For instance, supporting rural-urban migration could offer a potential route for supporting small-scale production. The remittances households receive from migrant members are not only used for immediate needs but reinvested into farming and improved agricultural technologies (Mendola, 2008; Ng'ang'a et al., 2016; Tshikala et al., 2019). National and local policies that facilitate migration and help movers maintain connections with their rural households - for instance, improved transport services, access to secure and well-paid jobs and reducing the cost of remittance transfers – could thus help boost rural economies and further support smallholder farming.

3. Limitations of the research

The research presented in this thesis was conducted within the context of a large-scale dryland restoration project (World Agroforestry, 2020). This meant I was able to analyse data collected from a large number of farms across a wide range of farming contexts. I was also able to co-locate my research sites with other research projects allowing me to draw on a diverse collection of datasets from the same rural communities. Nevertheless, working within the framework of existing projects presented several limitations and meant certain aspects of study design were not in my control.

One limitation is that farmers involved in the dryland restoration project and thus included in our sample are unlikely to be representative of the wider community, nor fully capture the heterogeneity of farm and farmer circumstances. Farmers engaged in the dryland restoration project were self-selected and the majority were female, aged between 35 and 54, married and had access to land. Even when attempting to use a more representative sampling frame for the aspirations survey in Chapter 5, our sample showed a strong bias towards women and older age groups, since children were in school, and men were often away working in towns and cities.

Working within the constraints of existing research projects meant that surveys were often designed for objectives other than those of this study, leading to unbalanced data that limited the numbers of observations and factors I could include in analyses and the statistical analyses I could perform. As already discussed, the planting basin monitoring surveys overlooked several explanatory factors that are likely to be important for explaining variation in yield response, such as soil texture, slope (Mupangwa et al., 2008; Nganga et al., 2019; Nyagumbo et al., 2016), erosion prevalence, and variation in farmers' management practices (Bunderson et al., 2017).

Large variation in how individual farmers had implemented and managed their basins is also likely behind the large amounts of noise and unexplained variation in our datasets. This thesis therefore illustrates several of the trade-offs between engaging large numbers of farmers in on-farm trials and understanding specific treatment effects (Laajaj et al., 2020). On the one hand, researcher-managed trials, offer more control over external factors and are well suited to understanding and isolating the biophysical impacts of treatments (Coe et al., 2019). On the other, more collegial and farmer-managed trials better reflect smallholder farming conditions and are well placed for exploring variability in treatment effect as experienced by farmers (Coe et al., 2019; Franzel and Coe, 2002). Both, however, are needed to provide farmers with relevant and effective recommendations for their circumstances. As discussed in Chapter 3, our farm-scale model has several shortcomings. These include: having been informed largely by secondary data collated and synthesised by researchers with limited input from farmers; oversimplification of the farming system (e.g., no consideration of intercropping or crop rotation), no exploration of quantification of uncertainty of model outputs, and a lack of robust model validation and sensitivity analysis. Nevertheless, many of these shortcomings could be addressed through future iterations of model development and use of participatory approaches.

The ability to generalise findings from this thesis to restoration efforts in other geographic locations is also limited by its focus on three counties in eastern Kenya and the performance of a single restoration practice and crop. While much of this thesis has focused on the use of planting basins for maize production, rural households in eastern Kenya typically grow a variety of crops, intercropping maize with legumes such as pigeon pea and cowpea. Integration of restoration practices such as basins with drought-tolerant crops such as sorghum (*Sorghum bicolor*) and millet (*Eleusine coracana*) could potentially offer greater benefits in terms of household food security and climate resilience than their use with only maize.

4. Towards a more integrative approach to research for development

While this thesis initially set out to assess the livelihood impacts of two restoration practices – planting basins and on-farm trees – it largely focused on the impacts and viability of planting basins. This was primarily because the trees planted as part of the planned comparison were still very young at the time of the study and had not yet started to produce. Nevertheless, the various approaches used throughout this thesis could easily be adapted to the evaluation of on-farm trees as well as other agricultural technological interventions, nor are they idiosyncratic to the drylands of Kenya. In this way, the methods used in thesis can be seen as a toolkit for evaluating the impact, trade-offs, and viability of agricultural innovations.

The need to combine approaches and methods is illustrated across chapters and findings from one chapter often informed the development of another. Yet, while this work is arguably interdisciplinary, Figure 6.2 outlines several entry points for further integration across chapters. These potential entry points largely centre on further development of the farm-scale model based on findings from other chapters, and its use within a participatory research setting.

For instance, developed prior to Chapters 4 and 5, our current model overlooks key gender dimensions. As is often the case with farm-scale simulation models (Micheletti and Elias, 2019), our model does not consider the labour implications of planting basins for individual household members, nor the distribution of costs and benefits from their use. Although it accounts for gender of household members in terms of daily grain demand, family labour is pooled, and men's and women's labour are not differentiated. As revealed by Chapters 4 and 5, in reality, individuals within the same households are likely to have different roles and responsibilities and contribute the household's livelihood strategy in distinct ways (Crossland et al., 2021a, 2021b). These Chapters highlight the need for explicit consideration of the gender roles and relations within the model and to link our findings back into the modelling process.

Similarly, while our model includes several livelihood components and their interactions, it assumes the household's primary objective is to invest in maize production, not off-farm income activities. Yet, as revealed by Chapter 5, households often have diverse livelihood aspirations even within agriculture, and different household members may wish to invest in different livelihood activities including off-farm work (LaRue et al., 2021; Mausch et al., 2021). An interesting application of our model could be to use it within a participatory setting to formulate aspirational scenarios with groups of farmers or households and assess the realisability of their various visions for the future, and how individual livelihood strategies and aspirations might play out at the household level.

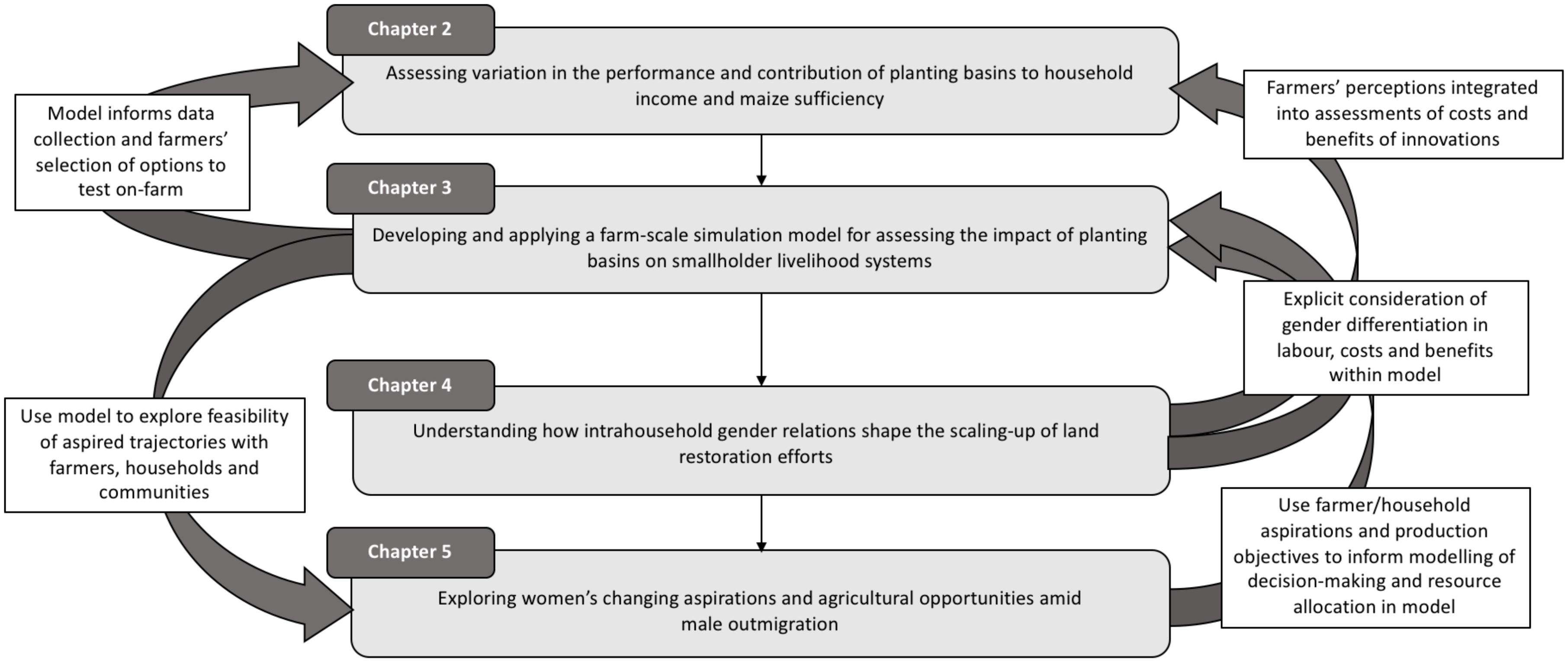

Figure 6.1 Proposed way forward for a more integrative, transdisciplinary systems approach to the evaluation of innovations.

As already discussed, there is a clear need to consider the values and perceptions of farmers in the evaluation of innovations (see section 1.3). Model development was largely informed by secondary data collated and synthesised by researchers with limited input from farmers. Taking a more participatory, co-learning approach to model development and validation, could thus help advance the saliency and legitimacy of the model and its outputs (Lynam, 2016; Vanclay et al., 2006). Through their involvement in the modelling process, participants are more likely to trust in a model's outputs and consider alternative courses of action in resource management. The process of building the model may also help improve their understanding of the system being modelled, and in some cases, the process of developing the model may be more valuable than the outputs from the model itself (Vanclay et a., 2006).

The value of the methods and approaches used in this thesis should also be judged in light of their contribution to the research in development framework proposed by Coe et al. (2014) and as outlined by the CGIAR Research Program on Forests, Trees and Agroforestry (CRP FTA, 2016) (see Figure 6.2). For instance, not only can data collected from planned comparisons help inform the development of APSIM-Simile livelihood models but model development process itself could highlight gaps in our understanding of key option-livelihood interactions, and further inform data collection. In turn, farm-scale models could be used to provide context-sensitive recommendations and even input for farmer-led participatory trials (i.e., planned comparisons). For instance, models such as that presented in Chapter 3 could be used with farmers to develop various option scenarios and to aid discussion and decisions over which options they would like to trial on their farms.

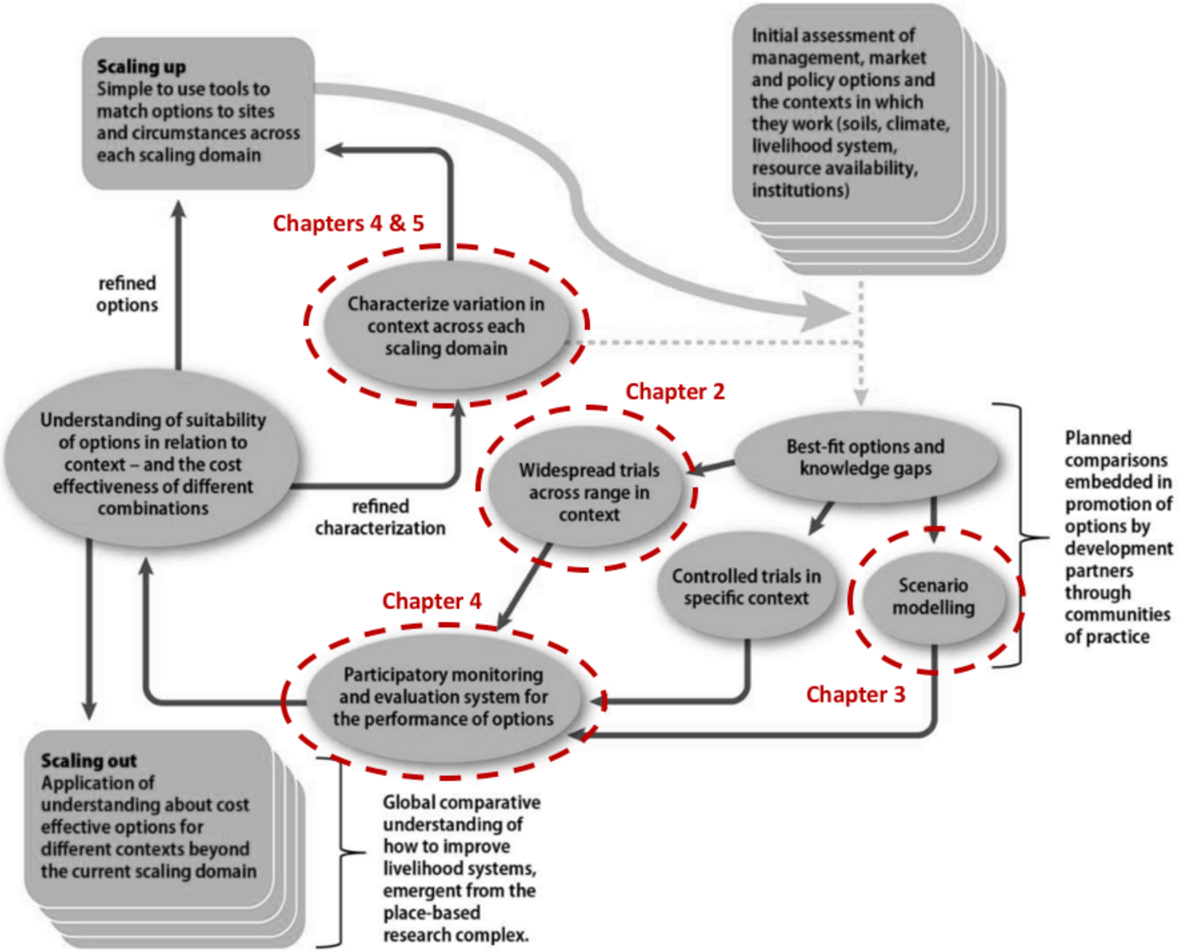

Figure 6.2 Role of thesis chapters in the context of the 'research in development' (RinD) approach (adapted from CRP FTA, 2016 and Coe et al., 2014).

5. Final conclusions

This thesis responded to the need for systemic approaches to evaluating agricultural innovations and attempted to embrace both the complexity and diversity of smallholder livelihood systems through its methods. Conducted in the context of a large-scale land restoration project in the eastern drylands of Kenya, my overarching goal was to assess the impact of on-farm restoration practices – planting basins and on-farm tree planting – on the livelihoods of smallholder farm households, so as to improve the specificity of recommendations and scaling of restoration efforts. While it is not yet possible to conclude whether the approaches used and insights from this thesis will lead to wider uptake of restorative practices, this thesis can be seen as an exploration of how we can approach complexity within agricultural systems research and speaks to a broader shift needed in the field of agricultural research and development.

In Chapter 2, I presented various analytical approaches to assessing the efficacy of planting basins for growing maize and revealed strong variability in yield response across farms. This variability in performance presents substantial risks for farmers when basins are promoted as a generalised recommendation. While understanding the causes of variation in yield response can help identify the conditions under which innovations are most likely to have a positive effect, this requires the collection of data on relevant factors. As demonstrated in this thesis, this can be challenging especially when engaging large numbers of farmers and encouraging on-farm adaptation of innovations. In Chapter 3, I developed a farm-scale model that extends the results from Chapter 2 and explores the impact of planting basins for two households with contrasting resource endowment. Model results underscored the need to evaluate innovations in a much broader sense than usually done and suggest that, although unlikely to lead to transformational change in terms of household income, integrating basins into current farming systems could provide a critical safety net in terms of household food security in the face of increasing climate variability.

Chapter 4 and 5 broadened the scope of my assessment and revealed heterogeneity also exists in the aspirations of those within households, and that women are likely to be important catalysts of agricultural innovation amid the increasing outmigration of men and feminisation of farm management. Chapter 4 also showed that the uptake of restorative farming practices is generally not a unitary decision made by individuals acting alone but involves some form of consultation between multiple household members, often husband and wife. Furthermore, these spousal relations can present a potential barrier to the uptake of restorative farming practices, particularly for women. This thesis thus demonstrates that successful restoration activity in the eastern drylands of Kenya will only be achieved with careful consideration of how gender dimensions feed into decision-making, and that employing an intrahousehold approach to restoration could increase the uptake, success, and equity of on-farm restoration efforts.

While the work presented is arguably interdisciplinary, in this final chapter I have laid out a vision for how to move even further towards an integrated and systemic approach. In this way, this thesis can be seen as an exploration of how we approach complexity within agricultural systems and a toolkit for evaluating the impact, trade-offs, and viability of innovations. It brings together alternative approaches to assessing agricultural innovations, and in doing so, stresses the need for development-focused agricultural research to step away from a fixation on differences in mean yield and embrace variability in innovation performance and complexity of smallholder livelihoods, not avoid it.

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Appendix 1: Planting basin planned comparison survey for Chapters 2, 3 & 4

Questions from OND 2017 ODK monitoring survey form. A similar set of questions were used in OND 2018 and OND 2019 monitoring surveys. The OND 2017 survey included questions of gender division of labour and decision-making over the planting basin planned comparison used in Chapter 4. For gender questions regarding the tree planting planned comparison used in Chapter 4, please see Magaju et al. (2019).

	Name, date & time
1.1	Enumerator name
1.2	Date
1.3	Time
	Location information
2.1	Household ID
2.2	Farmer's name
2.3	County
2.4	Sub-county
2.5	Ward/Division
2.6	Location
2.7	Sub-location
2.8	Village
	Respondent information
3.1	Gender of interviewee
3.2	Age of interviewee
3.3	Are you the household head or what is your relationship to him/her?
	Land preparation
4.1	What method do you normally use to prepare land before planting?
4.2	Was the plough with oxen owned, rented or borrowed?
4.3	Who is normally involved in this method of preparing land?
4.4	Who is normally part of the group?
4.5	Who is normally part hired labour?
	Decision making
5.1	Who decided on which PCs to be involved in?
5.2	Who decided on where and how many planting basins to dig?
5.3	Who dug the basins?
5.4	Who is normally part of the group?
5.5	Who is part hired labour?
	Tools
6.1	Did you already own the tools needed to dig the basins?
6.2	If no, how did you get the tools
6.3	Did you know about planting pits before the project?
	Planting basins number
7.1	How many basins do you have on your farm in total?
7.2	How many are 30x30?
7.3	How many are 60x60?
7.4	How many are 90x90?
7.5	How many are of other dimensions?
	Planting basins time
8.1	Have the planting basins changed the amount of time it takes to prepare the land?
8.2	Have the planting basins changed the overall amount of time you spend working on the farm?

8.3	Has this affected your ability to perform other tasks? If yes, which tasks?
8.4	How have you used this extra time?
	Farm labour
9.1	Who usually applies the manure/compost/mulch on the farm?
9.2	Who is usually part of the group?
9.3	Who is usually part of hired labour? (men/women/both)
9.4	Who usually does the planting on the farm?
9.5	Who is usually part of the group?
9.6	Who is usually part of hired labour? (men/women/both)
9.7	Who usually is involved in weeding on the farm?
9.8	Who is usually part of the group?
9.9	Who is usually part of hired labour? (men/women/both)
9.10	Who usually does the harvesting on the farm?
9.11	Who is usually part of the group?
9.12	Who is usually part of hired labour? (men/women/both)
9.13	Who usually applies pesticides/herbicides on the farm?
9.14	Who is usually part of the group?
9.15	Who is usually part of hired labour? (men/women/both)
	Number of treatment plots
10.1	How many treatment plots will you be assessing for this harvest survey?
	Treatment plots section (questions for each treatment plot assessed)
11.1	Assessment date?
11.2	What tillage practice did you use? (size of basin/usual practice)
11.3	What is the length of this treatment plot in meters?
11.4	What is the width of this treatment plot in meters?
11.5	How many people did it take to prepare the whole of this treatment plot for planting?
11.6	How long did it take them to prepare the whole of this treatment plot (in minutes)?
11.7	Over how many days did the preparation of this treatment plot take?
11.8	How long does it take **one** person to dig **one** basin of **this** size? (in minutes)
11.9	How often do you need to re-dig the basins?
11.10	Does it take a different amount of time to re-dig the basins than it does to dig them for the first time?
11.11	How long does it take one person to re-dig one basin? (in minutes)
11.12	How many basins in total are there in this treatment plot?
11.13	What method was used to prepare this plot?
11.14	Were the ox owned, rented or borrowed?
11.15	Crop currently planted in the plot?
11.16	Was it an improved or local variety?
11.17	Planting date?
11.18	Did you apply manure?
11.19	Did you apply mulch?
11.20	Did you apply fertilizer?
11.21	Did you apply pesticides?
11.22	Did you apply herbicides?
11.23	Have you already harvested the maize from this plot?
11.24	If yes, please estimate how much maize you harvested from the total area of this treatment plot (in kg)
	Harvest measurements for basin plots
	Within the treatment plot, randomly select a minimum of 5 planting basins to take harvest measurements from. If there are less than 10 basins in the plot, aim to take measurements from all of the planting basins. If there are more than 100 basins in the plot, aim to take measurements from 10 to 20 basins. Go to the first basin you have randomly selected and answer the following questions for this basin. Repeat for each individual basin you have selected (a minimum of 5 basins).
	Questions repeated for each selected basin
12.1	How many maize plants are there in this basin?
12.2	How many maize cobs are there in total?
12.3	Have they taken any cobs (green maize) from this basin?
12.4	Have they harvested any maize stalks (stover) from the basin?

12.5	Weigh the empty bucket or bag you will use to weigh the maize cobs. Make sure the bucket/bag is clean.
12.6	What is the weight of the bucket or bag in kg? (0.000 kg)
12.7	Now, harvest all cob within the basin and put them in the bucket/bag. Weigh the bag of cobs
12.8	What is the weight of the bucket/bag and the cobs? (0.000kg)
12.9	Harvest all maize stalks from the basin. Discard the roots and place stalks in a bag or tie in a bundle
12.10	What is the weight of the bucket or bag in kg? (0.000 kg)
12.11	Weigh the maize stalks using the scales
12.12	How much do the maize stalks weigh in kg? (0.000 kg)
	Harvest measurements for farmer practice plots
13.1	Walk to centre of the plot.
13.2	Use the 20m rope to measure a 5m by 5m square on the ground. Ask the farmer to help you.
13.3	If the farmers plot is smaller than 5x5m or there is a lot of biomass, then choose a smaller sized square
13.4	What size is your square plot?
13.5	If other, please specify
13.6	Then, for the whole of the square you have just measured, answer the following questions:
13.7	How many maize plants are there?
13.8	How many maize plants have cobs?
13.9	How many maize cobs are there in total?
13.10	What will you mainly use the maize and stalks for?
14.1	You can now start the harvest measurements for this square
14.2	Weigh the empty bucket/bag you will use to weigh the maize cobs. Make sure the bucket or bag is clean.
14.3	What is the weight of the bucket or bag in kg? (0.000 kg)
14.4	Now, put all cobs in the bucket or bag. Weigh the bucket/bag of cobs using the scales.
14.5	What is the weight of the bucket/bag and the cobs? (0.000kg)
14.6	Harvest all of the maize stalks from the square and place them in a bag or tie them in a bundle using string.
14.7	What is the weight of the bag in kg? (0.000 kg)
14.8	Weigh the maize stalks using the scales.
14.9	How much do the maize stalks weigh in kg? (0.000 kg)
14.10	Walk to centre of the plot.
14.11	Use the 20m rope to measure a 5m by 5m square on the ground. Ask the farmer to help you.
14.12	If the farmers plot is smaller than 5x5m, then choose a smaller sized square that will fit within the plot
14.13	What size is your square plot?
14.14	Then, for the whole of the square you have just measured, answer the following questions:
14.15	How many cobs did you harvest from the total area of the square?
14.16	Does this include green maize taken throughout the growing season?
	Food security questions
15.1	Will this season's harvest be enough to cover your household's consumption needs?
15.2	Do you think you will have surplus?
15.3	What will you do with this surplus?
15.4	How will you cope with this deficit?
15.5	Has your household received government assistance/food aid in the past 5 years?
15.6	Has your household received government assistance/food aid in the last 12 months?
15.7	Do you plan to dig more basins next season?
15.8	If not, why not?
15.9	If yes, which size?
15.10	How many do you plan to dig?

Appendix 2: Planned comparison maize harvest protocols

Maize yield measurement protocol

Objective: To compare productivity of the maize in planting basins and maize planted using the farmer method.

This protocol tells you how to take the harvest measurements for plots that have not yet been harvested. There are two methods. Which one you should use will depend on whether the treatment plot you are assessing contains planting basins (of any size) or the farmer's usual practice.

Equipment needed:

- Digital weighing scale
- Spare AAA batteries
- A clean bucket or bag for weighing cobs
- String to tie up maize stalks into bundles for weighing
- A 20-meter length of rope (please make a mark every meter along the rope)
- *Panga* for harvesting the maize stalks (ask farmer to help you with this)

Please note:

- There are different sets of questions within the ODK form for treatment plots with planting basins, farmer practice and those that have already been harvested. If the treatment plot has only legumes you do not need to take any harvest measurements but will still need to answer the questions in the ODK form.

- Please make sure you weigh the bucket or bag you are using for the survey (when empty and clean) and record its weight in kg. If it is very light and does not register on the scales, answer '0.000 kg' in the ODK form.

---------------------How to use the digital weighing scales---------------------

Turn on the scales by pressing the [ON/OFF] button.

Wait for the screen to load.

<< The screen should look like this image.

If it says 'Lb' or 'JIN' or 'OZ' at the bottom of the screen instead of 'Kg', press the [UNIT] button until it reads 'Kg'.

Before you start weighing, press the [TARE] button and make sure the screen reads '0.000 kg' before weighing.

Attach the bag or bucket or bundle of maize to the hook and lift them up using the scales.

[Make sure the screen says ‘0.000kg’ before you lift what you are weighing!]

<<< The scales will make a ‘beep!’ noise and a padlock sign will appear in the top of the screen, like in this image.

You can then take the reading from the scales and record the weight.

Once you have finished weighing, press [TARE] to unlock the screen and reset the scales to ‘0.000kg’ before weighing again.

Please make sure you turn the scale off when you are not using them (press the [ON/OFF] button).

-------How to take harvest measurements from treatment plots with planting basins------

Once you have answered the first set of questions within the ODK form you will be asked whether or not the plot you are assessing has already been harvested. If the plot has not yet been harvested and contains basins of any size, follow the steps below.

Step 1. Randomly select one planting basin from within the plot. Add a new group to the ODK form and answer all of the questions for this basin.

Step 2. Weigh the empty bucket or bag you will use to weigh the maize cobs and/or stalks. Enter its weight in kg into the ODK form (0.000 kg).

Step 3. Harvest every maize cob (try to leave the husks on the stalks) within the basin and put them in the bucket or bag.

Step 4. Weigh the bucket/bag of cobs using the scales and record its weight in the ODK form. This is the wet weight of the maize cobs from this basin.

Step 5. Empty the bucket or bag.

Step 6. Next, harvest all of the maize stalks in the square (ask the farmer to harvest them like they normally do, cutting them close to the ground). Put all of the maize stalks from the basin in the bag **or** tie them in a bundle using string. Discard the roots.

Step 7. Enter the empty weight of the bag/bucket into the ODK form again. If you have tied them up into a bundle using string enter ‘0.000’.

Step 8. Weigh the maize stalks using the scales and record their weight in the ODK form. This is the wet weight of the stalks from this basin.

Repeat the above steps for a minimum of 5 basins from this treatment plot.

If there are less than 10 basins in the plot, aim to take measurements from all of the planting basins.
If there are more than 100 basins in the plot, aim to take measurements from 10 to 20 basins.

If taking dry weights from this farm, keep 3 cobs + 3 stalks and follow the dry weight protocol

------------How to take harvest measurements from farmer practice plots ----------

If the plot is a **farmer's normal practice** plot and has **not yet been harvested**, follow the steps below.

Step 1. Walk to the centre of the plot. Use the 20-meter rope to measure a 5-meter by 5-meter square on the ground. If the farmers practice plot is smaller than 5-meters by 5-meters. Then choose a smaller sized square that will fit within the plot (for example, a 3-meter by 3-meter square).

Step 2. Then, for the whole of the square you have just measured, answer the questions in the ODK form.

Step 3. Weigh the empty bucket or bag you will use to weigh the maize cobs. Enter its weight in kg into the ODK form (0.000 kg).

Step 4. Harvest every maize cob (try to leave the husks on the stalks) within the square and put them in the bucket or bag.

Step 5. Weigh the bucket/bag of cobs using the scales and record its weight in the ODK form. This is the wet weight of the maize cobs from the farmer practice.

Step 6. Empty the bucket or bag.

Step 7. Next, harvest all of the maize stalks in the square (ask the farmer to harvest them like they normally do, cutting them close to the ground). Put all of the maize stalks from the square in the bag or tie them in a bundle using string. Discard any roots.

Step 8. Enter the empty weight of the bag/bucket into the ODK form again. If you have tied them up into a bundle using string enter '0.000'.

Step 9. Weigh the maize stalks using the scales and record their weight in the ODK form. This is the wet weight of the stalks from the farmer's practice.

You only need to take measurements for one square for this plot (farmer practice)

If taking dry weights from this farm, keep 3 cobs + 3 stalks and follow the dry weight protocol

Dry weight measurement protocol

Objective: To calculate the productivity of the planting basins and the farmer practice in terms of the dry weight of the yield.

For many reasons, the amount of water contained in the maize grown on different farms will be different. In order to be able to compare the maize yields between plots, farms and sites more fairly, we need to know how much water the maize from different sites contains. This is done by weighing a sample of the maize when it has just been harvested (the wet weight) and weighing it again when it is completely dry (the dry weight). We can then calculate the average moisture content of maize from each site.

Equipment needed:

- Data collection sheets
- Digital weighing scales
- Spare AAA batteries
- Brown paper bags to put stalk and cob (for each farm) samples in
- Pen to label paper bags
- Panga for harvesting and cutting the maize stalks into small pieces (ask farmer to help you with this)
- String to tie up the paper bags

Instructions:

When carrying out the harvest surveys, choose 5 farms that you will collect dry weight samples from. Make sure you choose farms that have not yet harvested their maize.

You will need to ask the farmer for permission to take some maize cobs and a sample of the maize stalks from their farm <u>or</u> ask if they are willing to keep the samples separate and safe until you return to reweigh them in 2 weeks' time <u>(they must not use them until after you have returned).</u> If you are taking them home, return them to the farmer after 2-3 weeks, once they have dried completely and you have reweighed them to get the final dry weight.

>> If the farmer has very few maize cobs, ask how many they would be willing for you to take/not use for 2 weeks – if they are not willing, use a different farm <<

At each of the 5 farms, carry out the following steps:

Step 1. Complete the harvest survey.

Step 2. Randomly select 3 cobs and 3 stalks from the planting basins and of 3 cobs and 3 stalks from an area under their normal farming practice. If the farmer has very few maize cobs, ask how many they would be willing for you to take from each plot (For example, 1 cob from the basins and 1 cob from their normal practice). Keep the cobs + stalks from the basins and from the farmers practice plots separate - Be careful not to mix them up.

Step 3. On the data collection sheet write your name, the date, the location of the farm, and the farmer's ID. Use a separate data sheet for each on the farms you are collecting the dry weights from.

Step 4. Weigh the empty brown paper bag and record its weight on the data collection sheet

Step 5. Put the maize cobs from the planting basins in one of the brown paper bags and label the bag with the farm number (1-5), the date, farmer ID, number of cobs, farm location, village and which treatment they are from (e.g. planting basins or farmer practice). For example:

Farm number 1, 14/2/18, ID: 1001, Cobs: 3, Mwala, Planting basins

Step 6. Punch a hole through the paper bag using a pen and attach it to the hook of the scales

Step 7. Make sure the scales read '0.000 kg' before weighing the cobs. Weigh the bag of cobs and record the weight in the data collection sheet. This is the wet weight of the maize cobs from the planting basins.

Remove the bag from the scales.

>> Repeat Steps 4 to 6 for the maize cobs taken from the farmers practice! <<
>> Remember to label the bag <<

Step 8. Take the maize stalks from the planting basins. Discard any roots and cut the maize stalks into small pieces using a panga (ask the farmer to help you with this).

Step 9. Weigh the empty brown paper bag and record its weight on the data collection sheet.

Step 10. Select pieces from across the stalk (bottom, middle, top) and fill one of the brown paper bags with the pieces (make sure you leave enough room so that you can close the paper bag).

Step 11. Label the brown paper bag containing the pieces of stalk from the basins with the farm number (1-5), the date, and farmers ID, farm location, the plot treatment (e.g. planting basins) and that the bag contains stalks.

Step 12. Punch a hole in the paper bag and attach it to the hook of the scales.

Step 13. Make sure the scales read '0.000 kg' before weighing. Weigh the bag of stalk pieces and record the weight in the data collection sheet. This is the wet weight of the maize stalk sample from the planting basins. Remove the bag from the scales.

>> Repeat Steps 7 to 11 for the maize stalks taken from the farmers practice! <<
>> Remember to label the bag! <<

>>> Take the cob and stalk samples home with you OR ask the farmers to keep they safe and dry them – they must not use the sample cobs/stalks until after you return to reweigh them <<

Once the samples are completely dry (approx. 2 weeks in the sun), reweigh them using the following steps:

Step 1. Reweigh each of the samples within their bag using the scales.

Step 2. Record the final dry weights for each of the separate samples using the data collection sheet for each farm.

Step 3. Then, for each of the maize cob samples, remove the grain from the cobs. Put the grain back in to the bag and reweigh. This is the dry grain weight. Record this in the data sheets for each of the maize cob samples.

>>Remember to return the samples to the farmer once you have taken the final dry weight <

Appendix 3: Gender interview questions for Chapter 4

Questions from the ODK form for the individual farmer interviews on gender dynamics surrounding the use and uptake of the planting basin and tree planting planned comparison for Chapter 4.

	Interviewee details
1.1	Household ID
1.2	Name of interviewee
1.3	Gender of interviewee
1.4	Age of interviewee
	Migration and off-farm activities
2.1	How many adult men are there in your household?
2.2	How many are usually available to work on the farm?
2.3	What do the men from your household do when they are not on the farm?
2.4	How many adult women are there in your household?
2.5	How many adult men are there in your household?
2.6	How many are usually available to work on the farm?
2.7	What do you do when you are not farming?
	Decision making on-farm in general
3.1	How are decisions about farming usually made in your household?
3.2	What types of decisions do you make on your own?
3.3	What types of decisions do you make with other household members?
3.4	Can you tell us about the work that you, specifically, do on the farm
3.6	Are there aspects of farming that men or women are discouraged from doing?
3.7	Are there things you would like to do on the farm but cannot because you are a woman/man?
	Involvement in the planned comparisons
4.1	Which of the following project activities are you involved with? (trees/basins/both)
4.2	The next set of questions focus on either the trees or basins. Which one would you rather talk about?
	Question asked to those only involved one of the comparisons
5.1	Why did you choose not to be involved in the tree planting? What would encourage you to plant trees?
5.2	Why did you choose not to be involved with the planting basins? What would encourage you to try basins?
	Questions asked to those who chose to talk about basins or only had basins
6.1	Were you aware of planting basins before the project?
6.2	Why did you decide to try them? What did you expect to achieve?
6.3	Has anything changed for you since you started using the basins?
6.4	Do you think the work involved with the basins has been worthwhile?
6.5	When you started, who was involved in the decision to use the basins? Did you have to ask for permission?
6.6	Where on the farm are the basins located? Why was this location chosen?
6.7	Who was involved in the decision on where the basins would be dug? Did you/they ask for permission
6.8	Who within your household do you think has put the most work in to the basins?
6.9	Who is usually responsible for land preparation using your usual tillage practice? (plough/hand hoe)
6.10	Has using basins changed the amount of time you spend working on the farm?

6.11	Have they effected your ability to perform other tasks? Which tasks?
6.12	If they reduced the time on the farm, how do you use this time instead?
6.13	Have the basins changed when other activities happen on the farm?
6.14	Are there advantages of the basins compared to your normal farming practice?
6.15	Are there specific advantages to any of the treatment options you have tested?
6.16	Are there disadvantages of the basins compared to your normal farming practice?
6.17	Are there specific disadvantages to any of the treatment options you have tested?
6.18	Who within your household has benefited the most from the basins?
6.19	Has the amount of food available for home consumption or sale changed as a result of the basins?
6.20	Who is involved in deciding how the produce grown within the basins is used?
6.21	Would you consider planting other crops within the basins? Which crops and why?
6.22	Do you plan on continuing to use the planting basins?
6.23	Are there other activities you would be interested in trying to improve productivity in your farm?
	Questions for farmers with trees only
7.1	Why did you decide to be involved with the tree planting? What did you expect to achieve?
7.2	Has anything changed for you since planting the trees?
7.3	Do you think the work involved with the trees has been worthwhile?
7.4	Who was involved in the decision to be involved in the tree planting? Did you have to ask for permission?
7.5	Where on the farm are the trees planted? Why was this location chosen?
7.6	Who was involved in the decision where on the farm to plant the trees? Did you have to ask for permission?
7.7	Who within your household has put more work in to the trees?
7.8	Has your involvement in the management of the trees changed since they were first planted?
7.9	Have the basins changed the amount of time you spend working on the farm?
7.10	Have they effected your ability to perform other tasks? Which tasks?
7.11	If they reduced the time on the farm, how do you use this time instead?
7.12	Has planting and management of the trees changed when other activities happen on the farm?
7.13	Are there advantages have you experienced as a result of tree planting?
7.14	Are their specific advantages to any of tree planting options you have tested?
7.15	Are there disadvantages to tree planting?
7.16	Are their specific disadvantages to the tree planting options you have tested?
7.17	Who within your household do you think will benefit the most from the trees?
7.18	How will produce from the trees will be used?
7.19	Who do you think will be involved in this decision? Will they have to ask for permission to use the produce?
7.20	Do you plan to plant more trees? Which options and why?
7.21	If no, why not and what would encourage you to plant more trees?
7.22	Are there other activities that you would be interested in trying to improve productivity in your farm?
	Questions for farmers with both of the planned comparisons
8.1	Which of the two practice (trees or basins) do you think will provide the most benefits for your household?
	Future aspirations
9.1	Were you born in this village?
9.2	Do you expect to continue living in this village?
9.3	Do you expect that your children will continue to live in this village?
9.4	Do you think your quality of life is better than your parents?
9.5	Do you think your children will have a better quality of life than you?
9.6	Are there other activities that you would be interested in trying to improve productivity in your farm?

Appendix 4: Gender focus group guide for Chapters 4 & 5

Gender focus group discussion guide

Purpose: The purpose of the focus group discussion is to capture diverse views around the gender differentiated aspects of restoration options being tested. The goal of the focus group is to not to identify one "right" answer but to see which views are more widely held around the following discussion topics and to clarify their meaning.

1. Decision making in farming management practices including changes that have occurred in the last five years, related or unrelated to the projects
2. Explore perceptions around joint decision making, focusing on 'how' decisions are made instead "who" makes them.
3. Impact of the planned comparisons on men and women's time and activities and the trade-offs they are willing to make
4. Implications for scaling up of restoration options. What strategies do men and women have available to overcome the challenges of scaling up restoration options

Introduction for all farmers

- As farmers arrive, create a roster of participants recording their name, age, and other relevant characteristics.
- Introduce ourselves and explain the purpose and expected duration of the session
- Explain that we will split up into groups to gather the particular views of men and women (because they may face different challenges and perceive different benefits from their participation in the projects activities).
- Explain that participants in each group should respond based on what people of the same sex do (men explain what men do and women what women do).
- Split farmers into groups by gender and start the discussions

Role of the facilitator

The role of the facilitators is to get the different participants talking, to bring out a range of perspectives, following up on comments to elicit what motivates participants' statements, and to review and gain concurrence about the positions expressed by the group in the summary period. The goal is to explore and document differences, even seeking consensus. Take notes as verbatim as much as possible, referring to the participants in the roster. Key words used in a local language should be recorded in that language and then translated/explained in English. Significant non-verbal reactions (e.g. body language, laughter) and tone of statements should also be recorded and if someone expresses something particularly well, this should be noted as a quote.

Remember to:

- Read the informed consent statement and obtain a verbal agreement from each participant.
- Encourage people to speak frankly and openly, be careful not to criticize them, whatever opinions they state. Instead, thank them when they share their views on sensitive issues as it helps us to better understand the problems they are facing.
- Encourage the participation of all participants by managing group dynamics, avoiding that the discussion be monopolized by one or more of the more vocal participants.

- Stress that topics raised within the group should be treated confidentially by all participants, so that people can feel comfortable expressing themselves. There are no right or wrong answers; the intention is just to understand people's different experiences and opinions

1. Introduction/ icebreaker

Ask the farmers to introduce themselves by giving their name and what their favourite fruit is.

2. Decision making in farming management practices

Please imagine a 5-step ladder, where at the bottom, on the first step, stand those women/men of this community with little capacity to make their own decisions about important affairs in their lives. These women/men have little say about if or where they will work, or about starting or ending a relationship with a spouse. On the highest step, the fifth, stand those who have great capacity to make important decisions for themselves, including about their working life and whether to start or end a relationship in their personal life.

1. On which step of this ladder would you position the majority of the women/men in the village today?
    a. The ratings should be done individually in private by the participants using small Post-its.
    b. The Post-its can be collected in a cup/bag and quickly posted next to the relevant ladder step so that all can see at a glance the general pattern of responses. The facilitator describes the pattern of responses and begin a discussion of the reasons for the ratings, starting first with the most prevalent response.

2. Why? Would any of you like to volunteer the reasons for your rating?

    Ladder of Power and freedom adapted from Petesch et al. (2018)

5	Power and freedom to make most decisions
4	Power and freedom to make many decisions
3	Power and freedom to make some decisions
2	Only a small amount of power and freedom
1	Almost no power and freedom to make decisions

3. Now please imagine the community 5 years ago when Uhuru first became president. On which step of this ladder would you position the majority of the women/men in the village 5 years ago?
4. Why? What has (or has not) changed for the women/men in this community? [note: you can probe for longer time period if no change has occurred]
5. Have these changes affected how decisions on farming practices are made?

Now we'd like to focus on decisions on farming management practices, including the basins, the planting of trees, and other practices that you and your family have adopted to improve productivity of your farm. From the past information we have collected, it seems that most farming decisions in this community are made jointly by husband and wife, with some exceptions such as women whose husbands work far away or widow.

6. Do you think this represents the reality of your community?
7. Think of a time you tried a new farming method and it worked well – what happened? Was it appreciated by others in your family or other community members? Did you gain more freedom to make decisions on the farm?

8. In households where women make most decisions, how are those women perceived by other women and men in their community? And how are the men in those households perceived by women and men in their community?
9. In households where men make most decisions, how are those men perceived by other women and men in their community? And how are the women in those households perceived by women and men in their community?
10. Do you think that the ways decisions about farming management are typically made are good or would you like to see this change? Why?

Now we want to ask about your views and experiences with other decisions in the household like decisions on income from farming. From the past information we have collected, it seems that unlike farming decisions, decisions about how to use income from farming are often made by men in consultation with other household members. But there are exceptions such as women who are widowed or whose husbands are not present on the farm.

11. Do you think this represents the reality of your community?
12. Are there sources of income that women alone decide on how to use without consultation?
13. Are there sources of income that men alone decide on how to use without consultation?
14. Are there sources of income that men and women typically decide together on how to use?
15. Do you think the way decisions over income are made in your community are good or would you like to see this change? Why?
16. Are there some households where women earn high incomes? What are the characteristics of these households and/or women (e.g. older women, widows, first wives, etc.)?
17. How are these women perceived by other women and men in your community? How are their husbands perceived by women and men in your community?
18. Do you think that the amount of income earned by women and by men in a household affects their relationship? If so, how?

3. Exploring joint decision making

Now I am going to read you some stories about four different women and men farmers and their situations regarding different agricultural activities. We want you to think about the men and women in your community and which farmer in the stories better represent the women and men of this community.

- Four women farmers, Jane, Faith, Veronica and Margaret attended a training on a new farming practice. After the training they went home and wanted to implement what they have learned:

    - Jane went straight to the field and started to try out what she learned. She did not have to consult anyone.
    - Faith talked to her husband and explained what she had learnt and how it would benefit the farm. He then agreed on trying the new practice and allowed her to make the decisions about it.
    - Veronica also talked to her husband, but he was not convinced because he did not attend the training. She insisted and after a long discussion the husband finally agreed but he then set the conditions for trying the new practice, like where on the farm and with which crops.
    - Margaret had to ask her husband for permission to apply her new knowledge but he refused immediately without further discussion. She could not try out the new practice.

- Four men farmers, Alex, Peter, James and Sammy, are considering buying tree seedlings from the local nursery to plant on their farms.

- Alex asked his wife what she thought about buying tree seedlings and which species would be best for their farm and where to plant them.
- Peter decided to buy the seedlings on his own but asked his wife about which species would be best for the farm and where to plant them.
- James also decided to buy the seedlings on his own. He came home and informed his wife about the seedlings and where he was going to plant them.
- Sammy bought the tree seedlings on his own, came home and planted them. He did not talk to his wife about any of these decisions.

19. Which farmer in the stories better represents the women and men of this community?
    a) Participants will choose individually in private by using small Post-its.
    b) The Post-its can be collected in a cup/bag and quickly posted next to the name/drawing so that all can see at a glance the general pattern of responses. The facilitator describes the pattern of responses and begin a discussion of the reasons for the ratings, starting first with the most prevalent response.

Now thinking about the experiences with planting basins and trees specifically:

20. In your community do women/men have to consult other members of their household before they start using planting basins?
    a. How might the discussion go? What would happen if they did not consult others or disagreed?
    b. What are the most common topics of disagreement? How is disagreement resolved?

21. In your community do women/men have to consult other members of their household when they started planting trees?
    a. How might the discussion go? What would happen if they did not consult others or disagreed?
    b. What are the most common topics of disagreement? How is disagreement resolved?

4. Impact of the options on time and labour

Now, present and explain the graphs displaying the monitoring results on how the time spent on farm and time preparing land having been affected. Explore how they would have answered and why.

22. Are they willing to continue digging the basins even if it requires more time spent on the farm?

Now, present and explain the graphs displaying the monitoring results on whether other task have been affected by the use of basins and which activities. Explore how they would have answered and why.

[For the men, explore what types of household chores they do]

23. In which cases would the extra time and effort spent digging basins not be worthwhile?
    [if trees only, ask only this question in regards to trees]
    Probe referring to situations in which, for example, household shores are neglected, or they don't receive any share of the produce/income.
24. What might stop women/men digging more basins /plant more trees on their plot? What can they do/ might they do to overcome these barriers? (If labour is the main constraint ask how have they coped, such as forming groups, and what are the advantages and disadvantages of these strategies)

25. Are there any circumstances in which a husband will help his wife with household chores? Are there any households where this happens in your community?

5. Impact of being involved in the planned comparisons

26. Has the way that you approach farming changed since being involved with comparing the different options on your farm? How?
27. Do you think you will continue to compare the performance of different farming practices, different crops/ tree species after the project finishes?

Bring the two groups together to share and conclude

- At the end, bring the groups together and ask one person (or several people if it helps increase their confidence) to present their sheet and results to all
- Ask if people saw differences in information, opinions or knowledge between groups
- Ask about why they think these differences exist?
- Conclude and summarize findings or differences for final confirmation. Take home messages are that (a) different groups may have different constraints and opportunities to improve their farm and their farming practices, (b) deciding and working together on how to manage the farm can help in overcoming those constraints and find better solutions for the challenges faced by farming households

Appendix 5: Migration interview guide for Chapter 5

Questions from the migration interviews used for chapter 5.

	Interviewee details
1.1	Household ID
1.2	Name of interviewee
1.3	Location
	Migrant details
2.2	When did they migrate/start leaving?
2.3	Where do they go and what do they do there?
2.4	How often do they return and why do they come back? [*weekly, monthly, which months & why*]
2.5	Who was involved in the decision for them to migrate? Did you discuss it as a household?
2.6	Can you think back to how life was for you before X left, and now?
2.7	How are things now? And how were they before? Can you see any differences?
2.8	Does anyone else in the household leave for several months of the year to earn income? Who?
	Aspirations and opportunities
3.1	What would you like to do in the future?
3.2	Do you plan on staying here on the farm? Why?
3.3	What about [migrant]? Do you know what they plan to do? Why
3.4	Does [migrant] have plans to return here and stay permanently in the future?
3.5	Do you plan on moving and joining them in [*location where migrant moved*]?
3.6	Do you think opportunities in agriculture have improved in the last 5 years? Why?
3.7	Do you think this differ for men and women?

Appendix 6: Migration focus group guide for Chapter 5

Questions from the migration focus group facilitation guide used for Chapter 5.

	Group participant information
1.1	Household ID of each attendee
	Patterns of migration
	First, we would like to talk about the types of migration within your community: who leaves, where they go and why they go
2.1	Does anyone here know someone who has migrated or has migrated themselves and returned? [*ask if anyone would like to tell us more about this – who left, where did they go and why*
2.2	What types of migration are common in this community? Who within the community usually leaves? [*probe for different types of migrants - gender, age*, *children, whole households]*
	Questions for each migration type
	Using a large piece of paper and pen, create a matrix displaying each type of migrant and their characteristics. For each type of migrant, they mention ask the following questions and fill in the matrix
3.1	Where do they usually go?
3.2	What do they do there? Is it easy to find work? How reliable is this work?
3.3	How often do they come back? [*weekly, monthly, yearly*]
3.4	Why do they come back at these times? Do they plan to return permanently one day?
	Changes in migration patterns
4.1	Has the number of people leaving changed over the last 5 years? Why?
4.2	Has the type of people leaving changed in the last 5 years? Why?
	Aspirations and opportunities
5.1	Why do you think people migrate? Does this differ for men and women? [*money, employment, aspirations, lack of land inheritance*, *land availability]*
5.2	Why do people stay within the community? Does this differ for men and women?
5.3	Do you think men and women have the same opportunities to migrate?
5.4	Do those who leave tend to come back and return to live in the community?
5.5	Why might they return? [*retirement, unsuccessful migration, buy land, marriage/start a family*]
5.6	Is it common for the rest of the household to join the migrant in the place they have moved to?
5.7	Would any of you like to migrate?
5.8	Do you think opportunities in agriculture have improved in the last 5 years?
5.9	Do you think this differ for men and women?

Appendix 7: Supplementary materials

Supplementary materials for Chapter 2

Table S2. 1 Number of plots assessed each season by treatment and site.

	Number of plots assessed						
	Machakos		Makueni		Kitui		All sites
	Mwala	Yatta	Kibwezi	Mbooni	Mwingi	Kitui Rural	
OND 2017							
Farmer practice	41	40	94	74	91	143	483
30x30cm basins	28	12	10	1	59	0	110
60x60cm basins	17	37	53	41	79	112	339
90x90cm basins	11	6	9	2	17	22	67
OND 2018							
Farmer practice	45	25	164	61	160	74	529
30x30cm basins	1	4	3	1	1	0	10
60x60cm basins	36	15	151	54	58	50	364
90x90cm basins	11	10	23	0	100	24	168
OND 2019							
Farmer practice	76	40	112	74	410	88	800
30x30cm basins	3	0	0	0	0	0	3
60x60cm basins	59	27	107	71	105	44	413
90x90cm basins	15	13	8	1	316	47	400

Table S2. 2 Additional days of maize household received from their basin.

	Number of additional days of maize						
	Machakos		Makueni		Kitui		All sites
	Mwala	Yatta	Kibwezi	Mbooni	Mwingi	Kitui Rural	
OND 2017	4 (0, 8)	1 (0, 3)	3 (0, 6)	17 (8, 43)	0 (0, 2)	4 (2, 10)	2 (0, 7)
OND 2018	1 (0, 6)	4 (1, 7)	7 (3, 18)	22 (12, 45)	1 (0, 3)	2 (1, 4)	4 (1, 10)
OND 2019	1 (-2, 5)	14 (6, 38)	7 (3, 10)	35 (19, 69)	21 (12, 35)	13 (7, 28)	18 (6, 34)

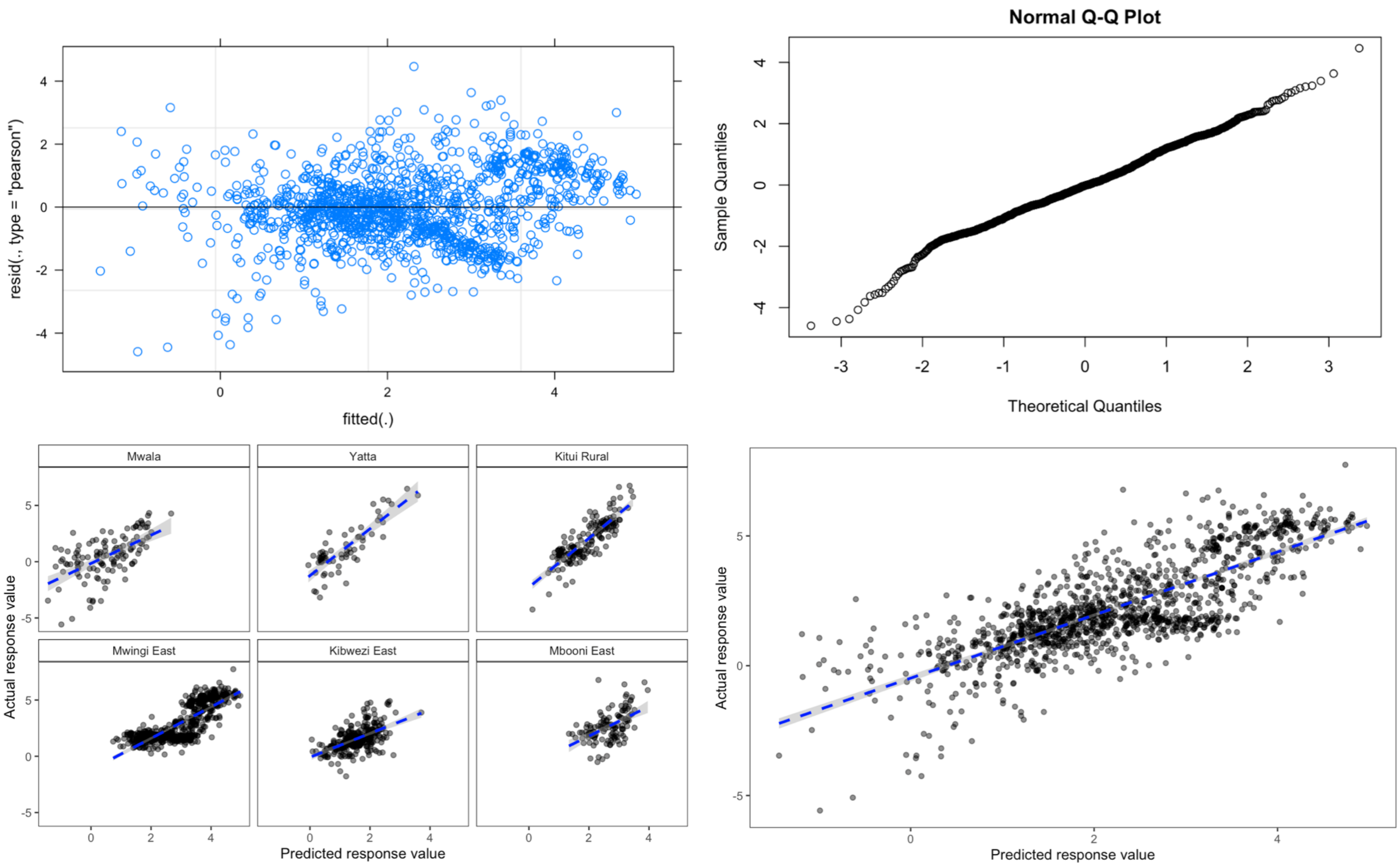
Statistics presented: Median (IQR)

Table S2. 3 Total number of planting basins per farmer.

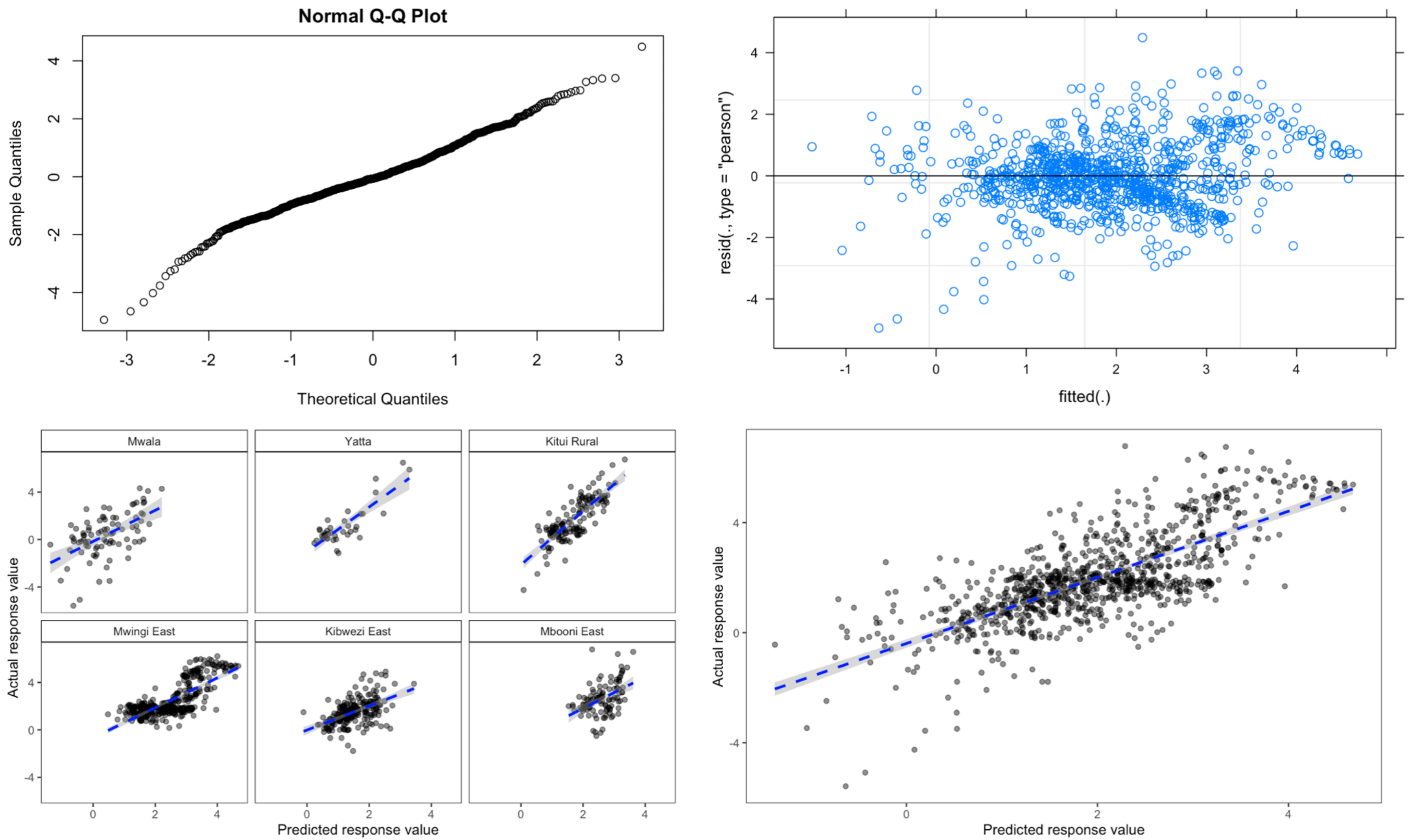
	Number of basins per farm						
	Machakos County		**Makueni County**		**Kitui County**		**All sites**
	Mwala	**Yatta**	**Kibwezi East**	**Mbooni East**	**Mwingi East**	**Kitui Rural**	
OND 2017							
Total number of basins	40 (3-300)	64 (5-231)	88 (5-646)	253 (15-2,231)	32 (4-250)	45 (2-300)	78 (2-2,231)
30x30cm	7 (0-95)	12 (0-140)	5 (0-94)	0 (0-12)	10 (0-40)	0 (0-0)	5 (0-140)
60x60cm	25 (0-226)	48 (0-155)	66 (0-620)	245 (0-2,231)	20 (0-230)	32 (0-200)	64 (0-2,231)
90x90cm	7 (0-100)	6 (0-78)	9 (0-240)	7 (0-236)	2 (0-26)	13 (0-300)	8 (0-300)
OND 2018							
Total number of basins	20 (5-124)	70 (10-222)	40 (7-1,500)	85 (6-1,920)	10 (2-60)	15 (3-300)	20 (2-1,500)
30x30cm	0 (0-12)	0 (0-72)	0 (0-30)	0 (0-50)	0 (0-2)	0 (0-8)	0 (0-72)
60x60cm	18 (0-112)	23 (0-91)	35 (0-1,000)	85 (6-1,870)	0 (0-60)	9 (0-114)	16 (0-1,000)
90x90cm	0 (0-52)	0 (0-100)	0 (0-180)	0 (0-100)	6 (0-50)	0 (0-300)	0 (0-300)
OND 2019							
Total number of basins	20 (5-360)	93 (5-2,400)	58 (8-1,522)	90 (10-1,922)	40 (7-2,015)	27 (7-600)	41 (5-2,400)
30x30cm	0 (0-18)	0 (0-189)	---	0 (0-45)	---	---	0 (0-8)
60x60cm	18 (0-360)	32 (0-250)	58 (0-1,522)	90 (0-1,877)	0 (0-100)	4 (0-300)	8 (0-1,500)
90x90cm	0 (0-52)	0 (0-175)	0 (0-380)	0 (0-10)	29 (0-2,015)	12 (0-600)	10 (0-600)

Statistics presented: Median (range)

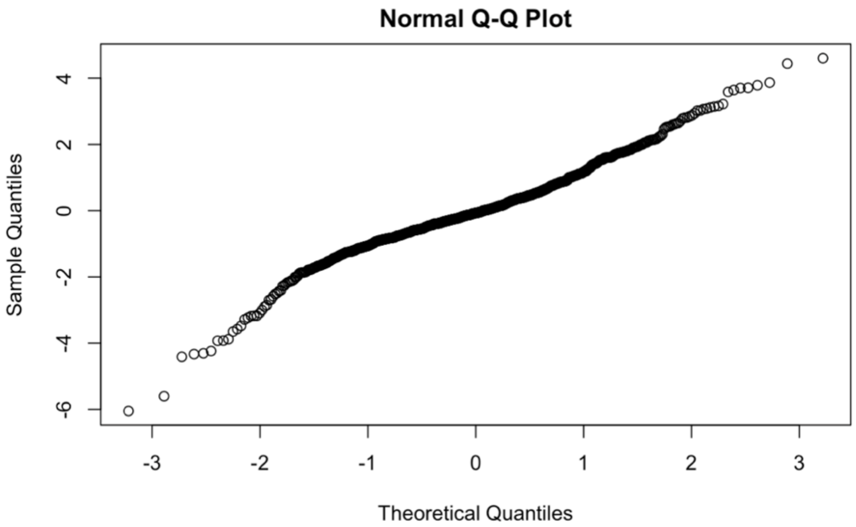
S2.1 Diagnostic plots for model 1

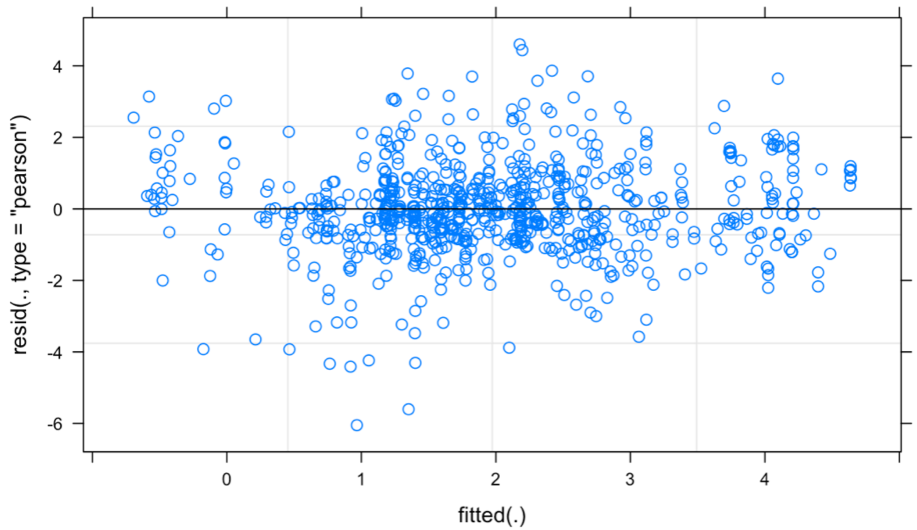


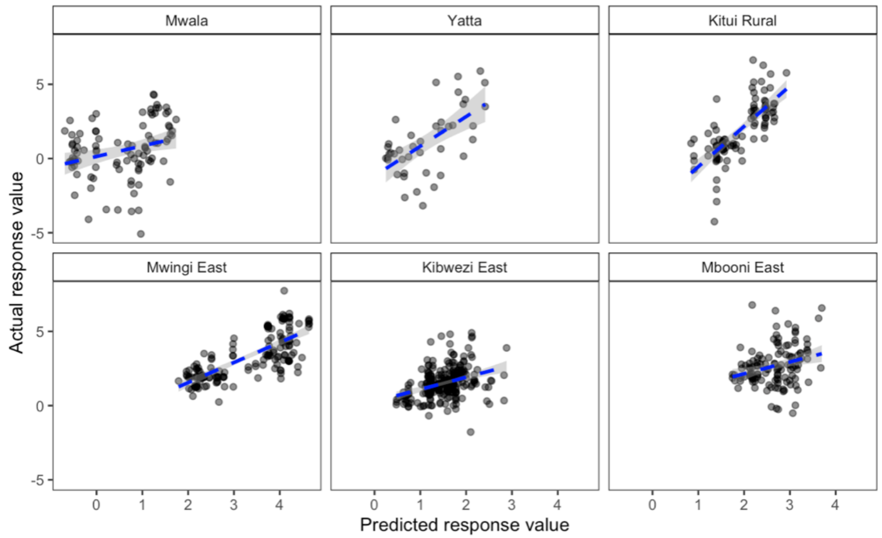
S2.2 Diagnostic plots for model 2

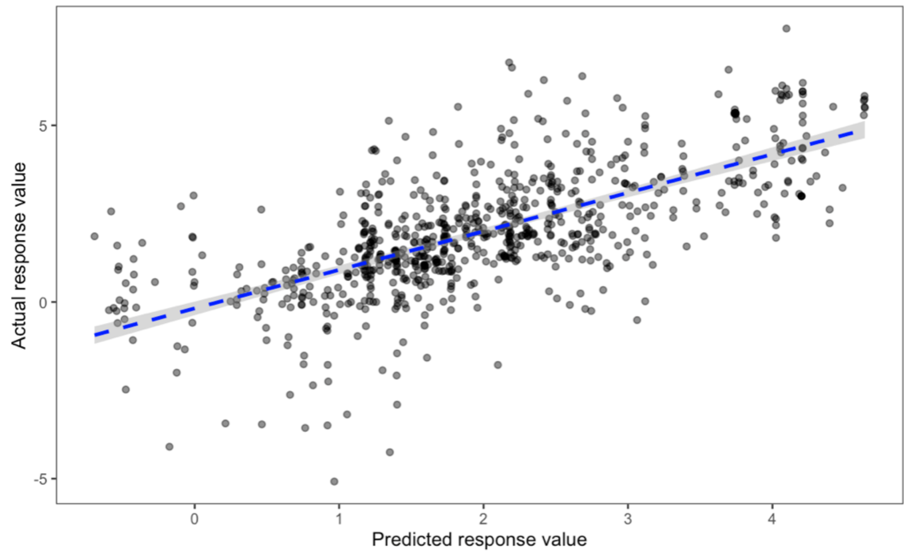


S2.3 Diagnostic plots for model 3

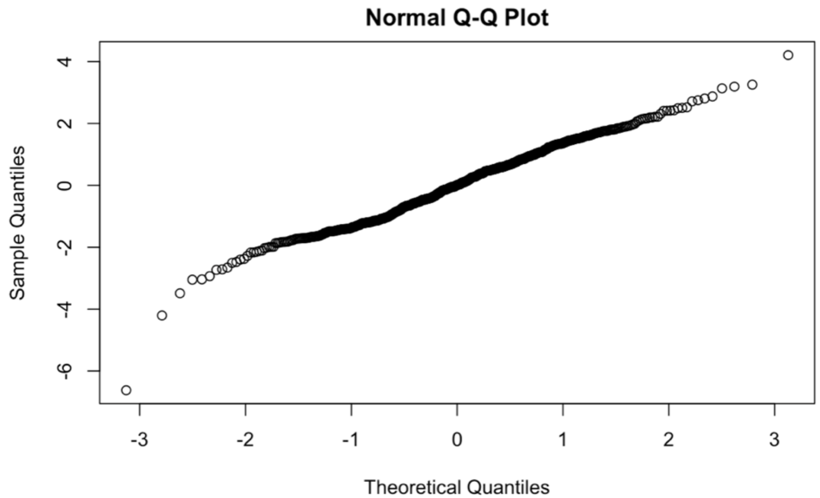


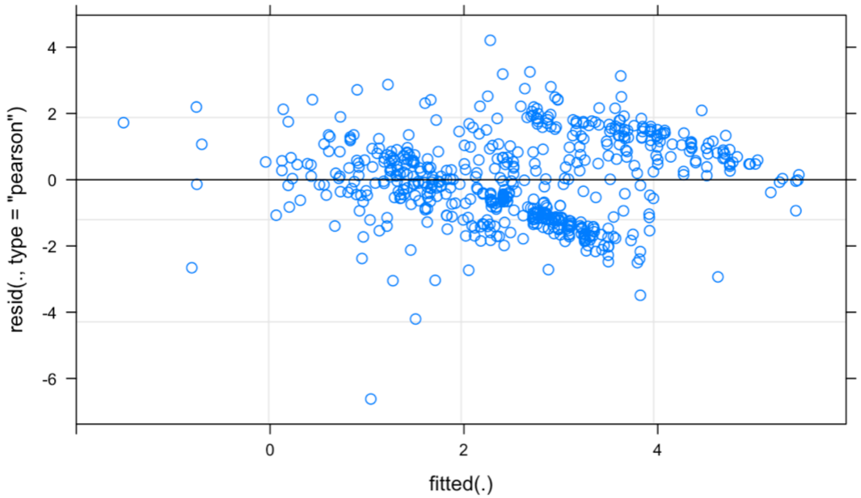


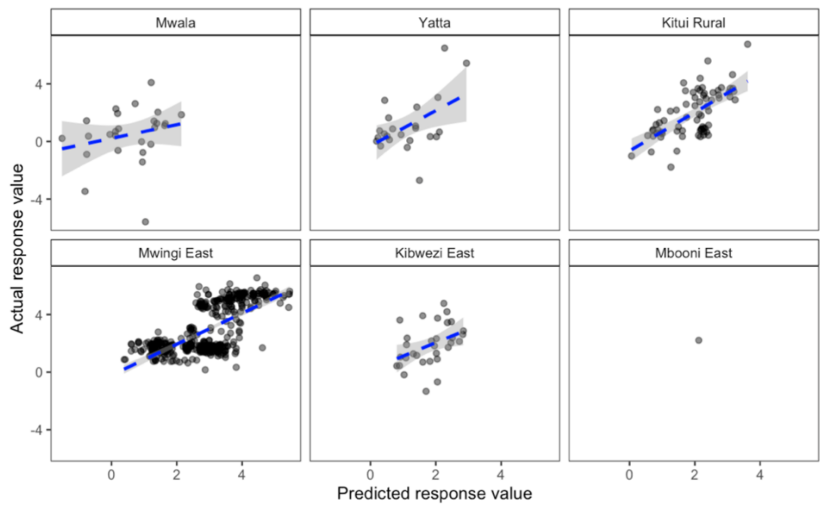


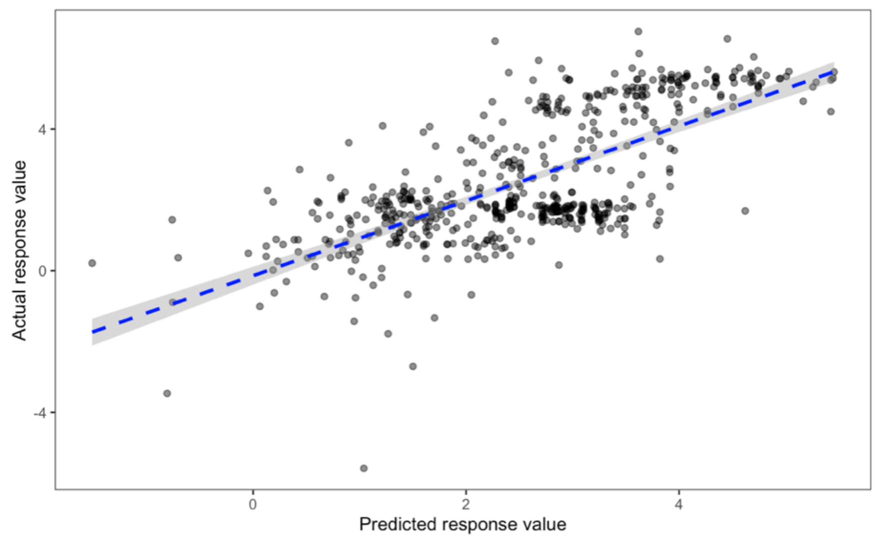


S2.4 Diagnostic plots for model 4









S2.5 Assumptions for variable costs used in profitability analysis

Hand hoe/plough cultivation: For OND 2017, we used the estimated time taken to cultivate the treatment plot using the farmer's usual tillage practice and scaled this to days per hectare. For OND 2018 and 2019, the size of each plot for farmer practice was not measured, so we used the median time taken for hand hoe and ox plough from OND 2017 instead (i.e., 10.42 days/ha and 2.19 days/ha, respectively).

Labour cost: Labour costs assume a day rate of 225 Ksh based on the basic wage for an unskilled labourer within the agricultural industry (KNBS, 2020).

Seed costs: The cost of seed was based on community facilitator estimates (70 Ksh per kg of local seed) and a plant population of 3.5 plants m^2 for all treatments.

Maize value: Based on estimates from local community facilitators for the price of maize during times of surplus (30 Ksh per kg).

Planting: Assumed to be 5.14 days/ha for basins based on Nyamangara et al. (2014). For farmer practice planting is assumed to be included in land preparation times as usually occur together.

Manure: For plots where manure was added, we assumed manure application to take 8.11 days/ha and 2.84 days/ha for farmer practice and basins, respectively, based on Nyamangara et al. (2014).

Weeding: We assumed most farmers weeded by hand and that this takes a similar amount of labour as hand hoe cultivation per hectare. We thus used the mean value from OND 2017 of 10.42 days/ha for hand hoe cultivation. Weeding basins was assumed to take half this time (5.21 days/ha) based on our discussions with farmers. Many women reported that weeding in the basins take substantially less time than their usual practice due to ease of weeding (soil is loose) and that there is less of a weed burden in the basins.

Harvesting: Maize harvest was assumed to take the same amount of time per hectare for all treatments. We used the mean days/ha from Mazvimavi and Twomlow (2009) of 11.97 days/ha.

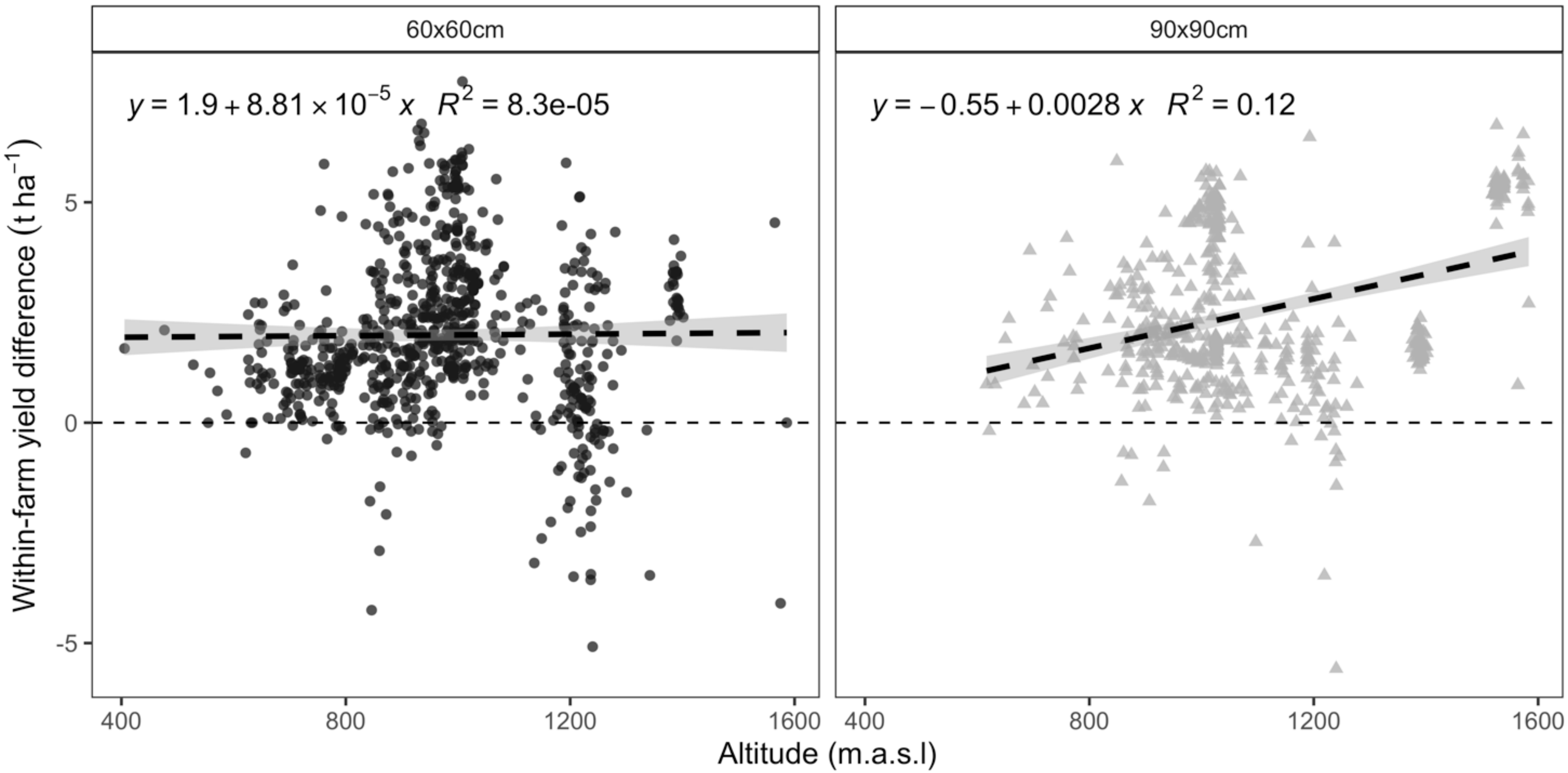


Figure S2. 1 Within-farm yield difference (t ha-1) from medium (60x60cm) and large (90x90cm) basins regressed against altitude.

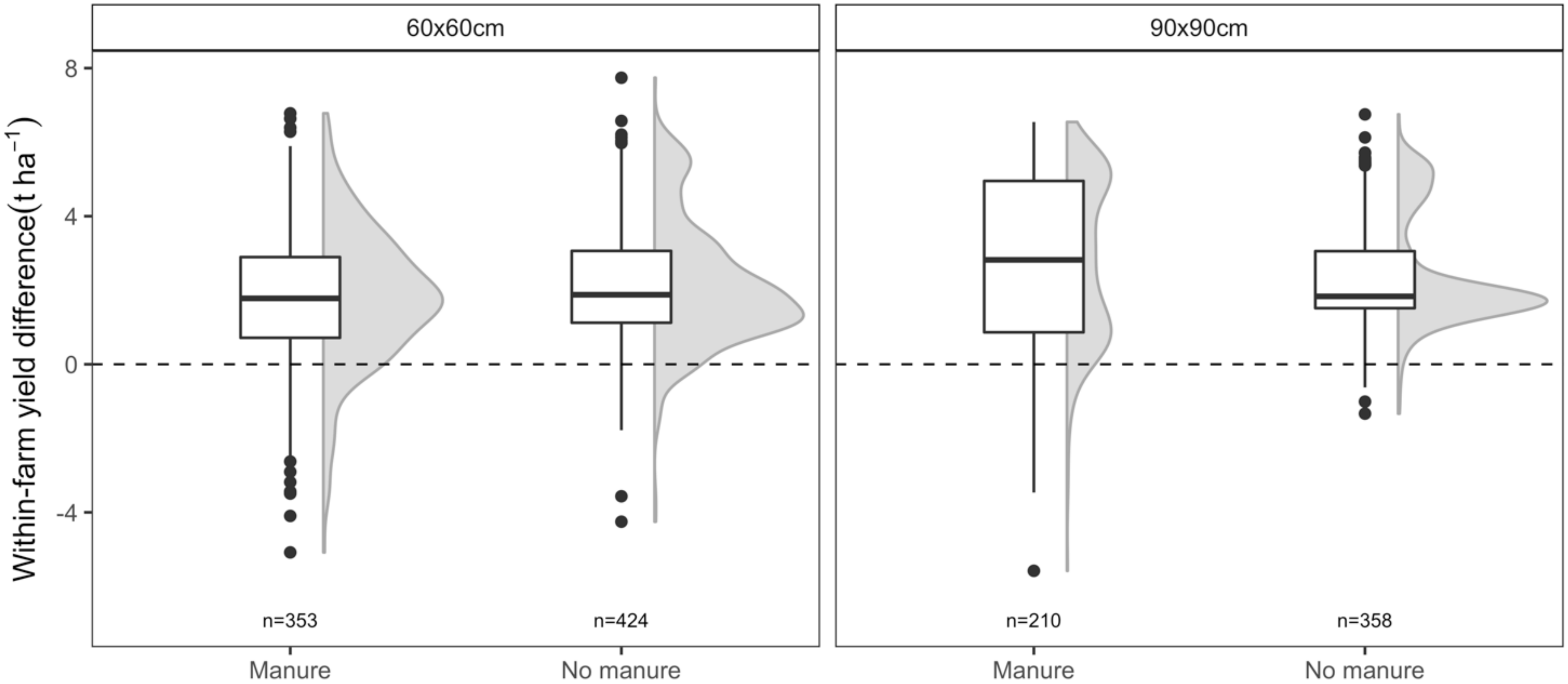


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Figure S2. 2 Within-farm yield difference (t ha-1) from medium (60x60cm) and large (90x90cm) basins with and without manure application.

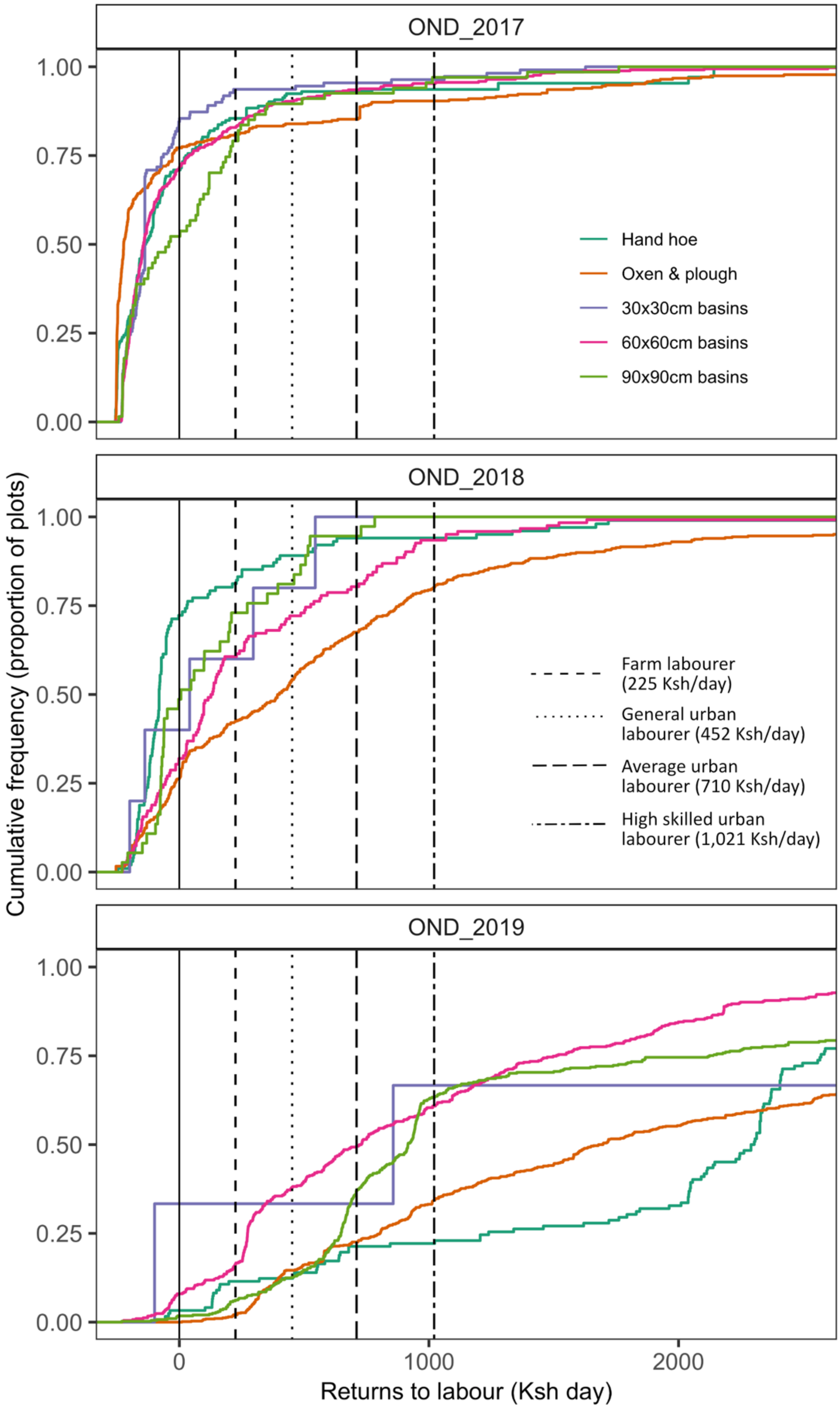

Figure S2. 3 Estimated returns to labour for each tillage system and monitoring season. Dashed lines show average wage rate for different occupations. Returns to labour for basin plots based on returns for re-digging basins.

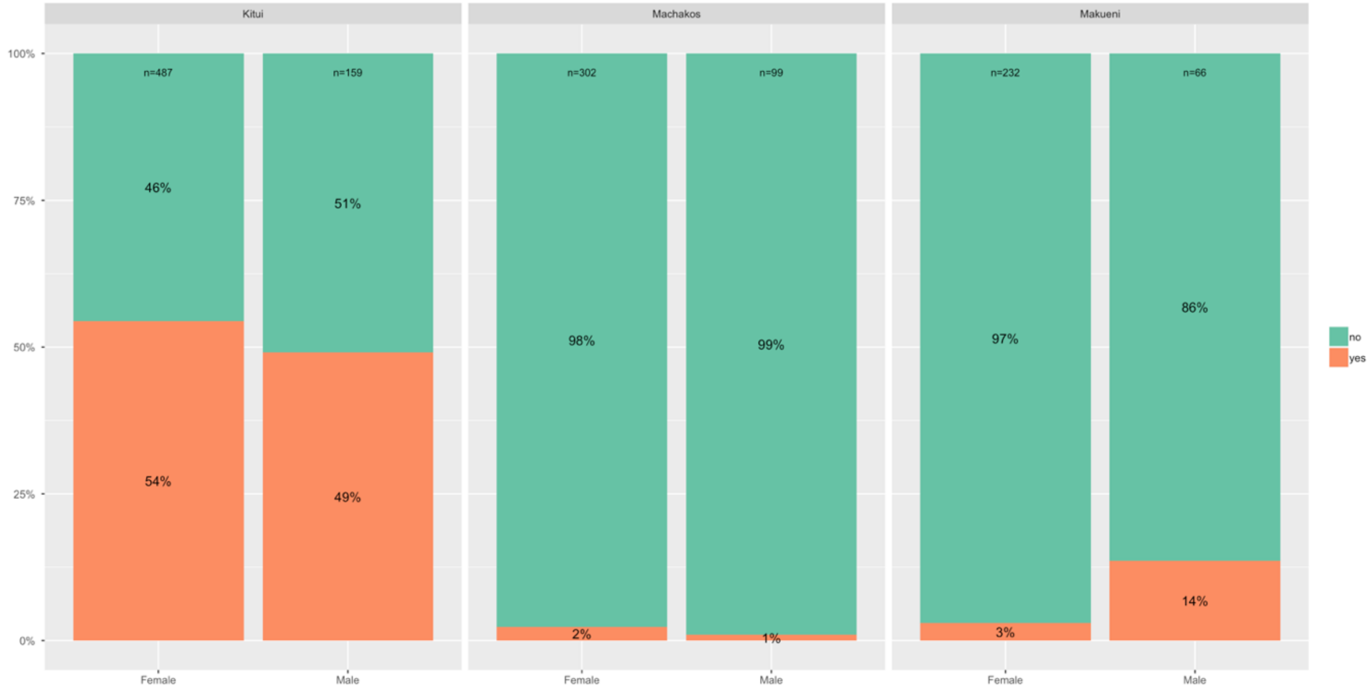

Figure S2. 4 Responses to the OND 2017 survey question: Have you received food aid in the past five years (Jan 2013 – 2018)? Kitui has the highest percentage of farmers having received food aid in the last five years. Machakos the least.

Supplementary materials for Chapter 3

Table S3. 1 Key parameters used in the model.

Variable	Units	Value	Description
Household submodel			
Off-farm wage	Ksh $hour^{-1}$	30.2	Based on a monthly basic wage of 7,241 Ksh for a general labourer outside of Nairobi (KNBS, 2019).
Hired labour wage	Ksh $hour^{-1}$	25-28	Based on a monthly basic wage of 6,736 Ksh for an unskilled farm labourer (KNBS, 2019).
Grain price	Ksh kg^{-1}	30-100	Estimates from field team.
Stover price	Ksh kg^{-1}	8.3-10	Estimates from field team
N fertilizer price	Ksh kg^{-1}	12.6	Based on estimate from field team of 3,500 Ksh per 5kg bag of DAP (and 18% nitrogen content)
Seed price	Ksh kg^{-1}	50	Estimate for local variety of maize from field team.
Crop model			
Digging basins	person-hours ha^{-1}	3472.0	Median time taken for one person to dig one medium sized basins (60x60cm) for the first time based on planned comparison survey data OND 2017 (see Chapter 2).
Repairing basins	person-hours ha^{-1} $year^{-1}$	1736.0	Median time taken for one person to repair one hectare of medium sized basins (60x60cm, i.e., 6,944 basins ha^{-1}) each year based on planned comparison survey data OND 2017 (see Chapter 2).
Ploughing	person-hours ha^{-1}	83.0	Median time taken for one person to prepare land using ox plough cultivation based on planned comparison survey data OND 2017 (see Chapter 2).
Hand hoeing	person-hours ha^{-1}	133.0	Median time taken for one person to prepare land using hand hoe cultivation based on planned comparison survey data OND 2017 (see Chapter 2).
Manure application to basins	person-hours ha^{-1}	64.9	Based on Nyamangara et al. (2014)
Manure application to farmer practice	person-hours ha^{-1}	22.7	Based on Nyamangara et al. (2014)
Fertilizer application	person-hours ha^{-1}	23.6	Based on Nyamangara et al. (2014)
Weeding farmer practice	person-hours ha^{-1}	133.0	Median time taken for one person to prepare land using hand hoe cultivation based on planned comparison survey data OND 2017 (see Chapter 2).
Weeding planting basins	person-hours ha^{-1}	66.5	Assumes weeding takes 50% less time compared to weeding under farmers usual practice based on discussions with farmers.
Cropland submodel			
Proportion of cultivated land under maize production	Fraction	0.63	Based on Brook et al. (2009).
Nitrogen content of farmyard manure	Fraction	1.28	Average based on several studies (Casu, 2018; Gowing et al., 2020; Lekasi et al., 2001; Ndambi et al., 2019; Zhu et al., 2020).
Livestock submodel			
Dung production	kg per kg of body mass day^{-1}	0.008	Base on Lekasi et al. (2001)

Fraction manure to collect during the wet season	Fraction	0.4	Assumes livestock kept in enclosure overnight
Fraction manure to collect during the dry season	Fraction	1.0	Assumes livestock kept in enclosure 24/7
Maximum body biomass for cattle	kg cow^{-1}	340	Reached over 4.5 years based on van Wijk et al. (2009)
Born body biomass for cattle	kg cow^{-1}	30	Based on van Wijk et al. (2009)
Dry season stover offer rate	kg per kg of body mass day^{-1}	0.03	Based on Rufino (2008) and Methu et al. (2001).

Table S3. 2 Soil chemical and organic values used in APSIM soil sub-model. Base characteristics for our study area were first extracted from SoilGrid™ (Poggio et al., 2021). We then adapted several values (highlighted in bold) based on data collected from Thange, Makueni County (L. Winowiecki 2019, personal communication) using the Land degradation Surveillance Framework (LDSF) (Vågen et al., 2010).

Depth (cm)	pH	Carbon (total %)	SoilCNRatio (g/g)
0-15	**6.68**	**0.973**	**10.806**
15-30	**6.68**	**0.973**	**10.806**
30-45	**6.65**	**0.823**	**10.288**
45-60	**6.65**	**0.823**	**10.288**
60-80	6.33	0.577	9.600
80-100	6.38	0.479	9.600
100-120	6.41	0.423	9.600

Table S3. 3 Annual maize grain production and within-year difference compared to baseline scenario.

	Scenario			
	Baseline	**Baseline+N**	**Basins**	**Basins+N**
Lower resource endowed household				
Grain production (kg farm year)	233 (0, 840)	205 (0, 944)	350 (59, 1,003)	344 (32, 976)
Within-year difference	---	0 (-161, 442)	116 (-16, 230)	108 (32, 152)
Grain bought (kg farm year)	190 (0, 437)	175 (0, 437)	17 (0, 344)	63 (0, 361)
Within-year difference	---	0 (-235, 87)	-52 (-297, 0)	-48 (-297, 0)
Grain sold (kg farm year)	0 (0, 54)	0 (0, 290)	0 (0, 197)	0 (0, 253)
Within-year difference	---	0 (0, 143)	0 (0, 200)	0 (0, 279)
Higher resource endowed household				
Grain production (kg farm year)	268 (1, 1,408)	210 (0, 1,897)	490 (82, 1,638)	505 (50, 1,557)
Within-year difference	---	-37 (-1,148, 761)	183 (-46, 743)	172 (-10, 812)
Grain bought (kg farm year)	103 (0, 357)	183 (0, 429)	0 (0, 178)	0 (0, 189)
Within-year difference	---	35 (-240, 306)	-87 (-340, 0)	-87 (-309, 0)
Grain sold (kg farm year)	0 (0, 829)	0 (0, 1,250)	45 (0, 1,023)	38 (0, 1,016)
Within-year difference	---	0 (-562, 737)	6 (-109, 602)	0 (-83, 667)

Statistics presented: Median (Range)

Table S3. 4 Annual maize stover production and within-year difference compared to baseline scenario.

	Scenario			
	Baseline	**Baseline+N**	**Basins**	**Basins+N**
Lower resource endowed household				
Stover production (kg farm year)	211 (0, 366)	259 (0, 592)	214 (28, 398)	237 (16, 395)
Within-year difference	---	17 (-5, 51)	25 (8, 42)	40 (-113, 311)
Stover sold (kg farm year)	180 (0, 366)	259 (0, 463)	209 (28, 398)	218 (16, 395)
Within-year difference	---	40 (-113, 231)	20 (-5, 51)	25 (8, 38)
Higher resource endowed household				
Stover production (kg farm year)	769 (359, 1,522)	609 (0, 2,380)	824 (137, 1,491)	868 (108, 1,579)
Within-year difference	---	30 (-259, 654)	57 (-288, 732)	112 (-717, 858)
Stover bought (kg farm year)	3,837 (2,804, 6,302)	3,837 (2,213, 6,470)	3,246 (2,509, 6,361)	3,224 (2,509, 6,204)
Within-year difference	---	-148 (-590, 2,361)	-295 (-2,509, 148)	-190 (-2,509, 148)

Statistics presented: Median (Range)

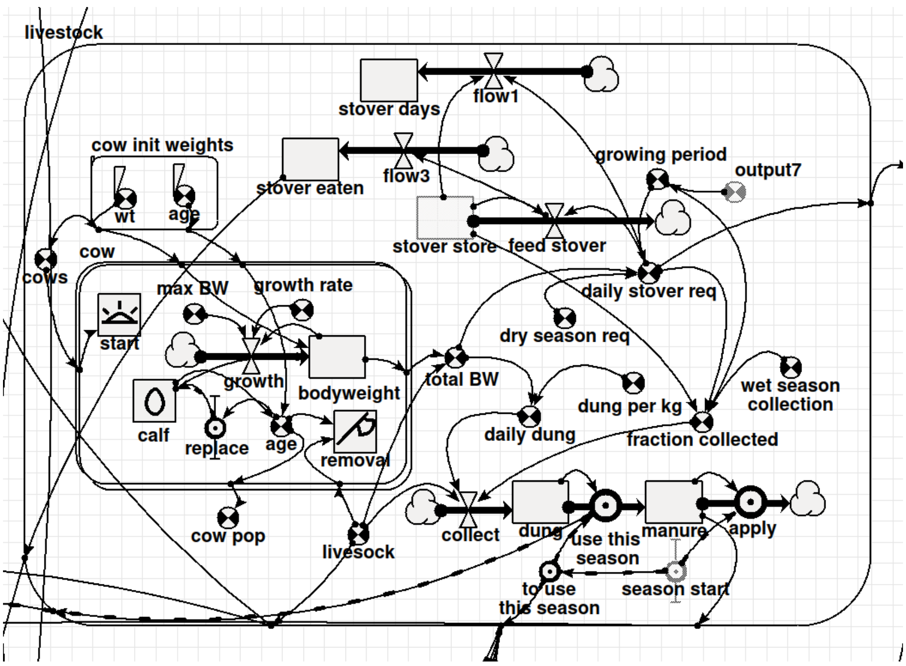

Figure S3. 1 Example of Simile modelling interface using the livestock submodel of the APSIM-Simile farm-scale model described in Chapter 3.

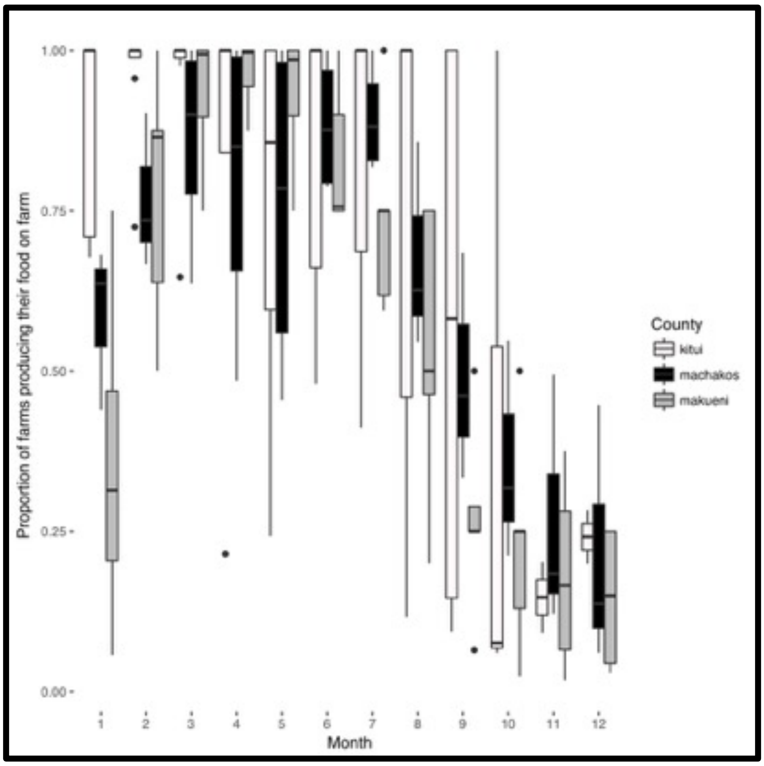

Figure S3. 2 Proportion of households producing their own food throughout the calendar year. Plot produced by Winowiecki (2019, personal communication) using household survey data (Winowiecki et al., 2019).

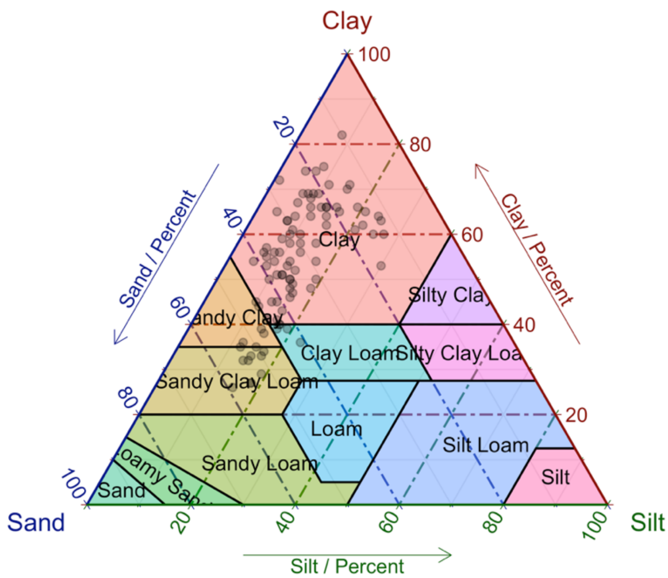

Figure S3. 3 USDA textual classification for soils collected from Thange, Makueni County (L. Winowiecki 2019, personal communication).

Appendix 8: Stakeholder summaries

Much of this thesis has centred on how we can improve the way we assess agricultural innovations and on learning within the research in development process. Here, I summarise what different stakeholders can take away from my research. Given that RinD approaches embed research within development activities, it should be noted that many of these take aways are likely to be relevant across stakeholder groups and are not necessarily exclusive.

Agricultural researchers

- On-farm restoration practices, such as planting basins, can provide substantial production increases for some farmers and substantial losses for others. Understanding the sources of this variation and the environmental and management conditions under which different restoration options perform best, could allow for better targeting of innovations to different farming contexts and reduce the risk farmers face when adopting new practices. This requires moving beyond average yields and assessing variability in option performance, but also accepting that farmers modify practices and adequately documenting these adaptations. For instance, some farmers have modified the basin technology to cope with heavy rainfall and avoid waterlogging, combined basins with supplementary irrigation, and are using basins to grow higher value crops.
- For restorative farming practices to be widely adopted they not only need to be productive and profitable they also need to be attractive within the broader context of smallholder livelihood systems. Farmers may be more interested in performance metrics, such as additional days of food for their family, income per capita, labour savings, increased resource use efficiencies and yield stability, rather than agricultural productivity alone. Researchers thus need to take a livelihoods perspective when assessing innovations and translate field scale metrics into farm scale metrics that are meaningful to households and their members. Farm-scale simulation models provide a useful tool for such assessments but even simple arithmetic and back of the envelope calculations can be a helpful first step towards more farmer-relevant assessments.

Development actors and NGOs

- Smallholder farmers are a diverse group, differing in their demands, opportunities, and constraints. Scaling restoration will require local adaptions of agricultural practices that respond to this fine scale variation in farm and farmer circumstances. Taking a research in development approach and collaborating with farmers and researchers to understand what works best, where and for whom, can help development actors and NGOs to move away from providing generic recommendations to more nuanced, context-specific suggestions for farmers. For instance, based on data collected from on-farm planned comparisons, basins provided greater gains in maize yield for farmers located in Makueni and Kitui counties compared to farmers in Machakos County. This is likely due to differences in local agroecological conditions such as slope, altitude, and soil texture. Planting basins are likely to better suited to farmers in Makueni and Kitui and present greater risk when adopted by farmers in Machakos.
- While restoration options such as planting basins may help buffer against climate variability and provide a safety net in terms of food security in times of drought, the adoption of a single practice alone is unlikely to transform rural livelihoods and lift households out of poverty. To improve the transformative potential of restoration practices, they may need to be combined and complemented with additional innovations, both on and off the farm. For basins, this could include finding ways to mechanise their construction and reduce their labour requirement; using basins to grow higher value crops other than maize; integration with rain water harvesting and supplementary irrigation; providing timely and accurate weather forecasts; and using improved agronomic practices, such as diversifying crop rotations, intercropping, judicious use of inorganic fertilizers, and increased application of organic inputs, to help increase and maintain soil organic carbon and fertility.
- In the eastern drylands of Kenya, the uptake of restorative farming practices is generally not a unitary decision made by individuals acting alone but involves some form of consultation between husband and wife. Thus, uptake of restoration practices may be constrained by the fact that only one household member usually attends training workshops. Consequently, projects employing an intrahousehold approach to restoration and engaging the wider household in training events and dissemination are likely to increase both the uptake of restoration practices and the success and equity of restoration efforts.

- Women are likely to be important catalysts of agricultural innovation amid the increasing outmigration of men and feminisation of farm management in eastern Kenya. When women attend agricultural workshops and are allowed to implement their knowledge, they can gain more confidence and recognition that can lead to greater agency in farming decisions. Through integrating gender-transformative approaches and using project activities to facilitate critical awareness and discussion of gender-inequitable relations, restoration initiatives could not only overcome gender-based constraints to scaling-up on-farm restoration efforts but provide a platform for social learning and the transformation of inequitable gender relations.

Local government and extension services

- Despite increasing rural-urban migration and the variable returns from rain-fed agriculture, smallholder farming will likely continue to play an important role in the livelihoods of those living in the drylands of eastern Kenya. When households invest in non-farming activities such as migratory wage labour, they often choose to keep one foot in farming, retaining land as a safety-net in the face of job insecurity, for their retirement, or because they culturally identify as farmers. Effective policies are therefore needed to support smallholder producers and increase both the profitability and ecological sustainability of small-scale farming systems.
- Given that restoration practices are often knowledge intensive, improving the access of farmers, especially women, to training and information on the use and management of restoration options would likely improve uptake and the efficacy of these practices. Potential cost-effective ways of improving extension services might include building collaborative partnerships between local government, research institutions, NGOs, and other development actors to scale land restoration efforts, or through use of innovative extension models such farmer-to-farmer learning and using information and communications technologies, such as mobile phone and app-based platforms, to disseminate knowledge.
- Smallholder farmers might also benefit from non-agricultural focused policies. For instance, supporting rural-urban migration could offer a potential route for supporting small-scale production. The remittances households receive from migrant members are not only used for immediate needs but reinvested into farming and improved agricultural technologies. National and local policies that facilitate migration and help

movers maintain connections with their rural households - for instance, improved transport services, access to secure and well-paid jobs and reducing the cost of remittance transfers – could thus help boost rural economies and further support smallholder farming.