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Smallholder farm management and priorities

Balancing productivity, livelihood, climate adaptation and ecosystem services

Ylva Nyberg

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Cover: Photos from Western Kenya from upper left: sweet bananas, shade tree, flowering tree (*Senna spectabilis*), children fetching water in Kisumu County, a man's hands during a group interview, passion fruit flower (*Passiflora edulis*), smallholder farming landscape in Trans Nzoia County, myself (Ylva Nyberg) between group interviews in Trans Nzoia County, fodder shrub leaves (*Calliandra calothyrsus*), common weed flower (*Vernonia* spp.), seeds (*Sesbania grandiflora*), flower of *Opuntia vulgaris*, zero-grazing calf, soil pit, one of the monitored farms.

(photos: Y. Nyberg and one (including Ylva) was taken by E. Laszlo Ambjörnsson)

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Errata for
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Location	Currently	Should be
Page 2, Cover	sweet bananas	sweet bananas (*Musa* spp.)
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Page 8, 4.3.3	Agriculture	Agricultural
Page 12, II	the senior author	one co-author
Page 16, KACP	Agriculture	Agricultural
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Page 41, 3.3.4 #1, row 9	practices including agroforestry	practices and agroforestry
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Page 68, Figure 14	% of farms with differnt levels	% of farms with different levels
Page 74, #2, row 13	all other practice	all other practices
Page 105, Popular Science summary #1, row 6	and maintain	and produce
Page 105, Popular Science summary #2, row 17	or savings.	and savings.

Location	Currently	Should be
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Paper IV, page 2, #2, row 1	Agriculture	Agricultural
Paper IV, page 2, Characteristics of the…, row 1	Agriculture	Agricultural
Paper IV, page 5, #2, row 14-17	Eucalyptus spp. and project farms had more N-fixing species like Sesbania sesban, Acacia spp. and Calliandra spp. The most common species overall were Grevillea robusta, Markhamia spp. and Albizia spp.	*Eucalyptus* spp. and project farms had more N-fixing species like *Sesbania sesban*, *Acacia* spp. and *Calliandra* spp. The most common species overall were *Grevillea robusta*, *Markhamia* spp. and *Albizia* spp.

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Abstract

Smallholders in sub-Saharan Africa are highly vulnerable to climate change, but also have good potential for improving production. This thesis examined how Kenyan smallholders manage their farming systems to adapt to rainfall variability and improve productivity, while also maintaining sustainable delivery of multiple ecosystem services. The study covered a gradient from Kisumu by Lake Victoria to Trans Nzoia in the Highlands. Awareness and use of adaptation and coping measures were studied through group and individual interviews. Effects of tree and livestock density on ecosystem services and farm priorities were explored on 20 farms. The influence of the Kenya Agricultural Carbon Project was assessed, using uptake of sustainable land management practices, maize yield, food self-sufficiency and savings as indicators.

Smallholder farmers were aware of local climate change and measures that can assist in adaptation, but uptake of these measures was limited by lack of money, knowledge and labour. Men had higher education, better access to advisory services and more time for social networks, and used more adaptation measures than, especially, low-educated women. Farmers with access to regular advisory services used greater numbers of more effective measures. Maize yield was positively related to terracing and inclusion of trees (agroforestry). Higher tree density increased the workload, but also the proportion of on-farm income, and trees were important for cultural ecosystem services.

Thus smallholders will not adopt more sustainable practices unless they have the means (labour, land, capital) and the knowledge that the benefits will exceed the costs. A holistic and inclusive advisory approach, focusing on low-educated women and promoting synergistic measures, diversified farming systems and means to overcome barriers to adoption of sustainable practices, could help smallholders balance adaptation, productivity and other ecosystem services for a sustainable livelihood.

Keywords: advisory service, coping, gender, indicators, KACP, Kenya, labour, learning source, limitation, sustainable

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Hur hanterar småskaliga jordbrukare balansen mellan matproduktion, försörjning, klimatanpassning och andra ekosystemtjänster?

Sammanfattning

Småskaliga jordbrukare i Afrika söder om Sahara är mycket sårbara för klimatförändringar. Avhandlingen studerade vilka åtgärder bönder i Kenya använder för att anpassa sin jordbruksproduktion till varierande nederbördsförhållanden och för att öka produktiviteten på sina gårdar på ett hållbart sätt samtidigt som de genererar ekosystemtjänster. Studien har utförts i ett område från Kisumu vid Viktoriasjön till Trans Nzoia på höglandet. Medvetenhet om och användning av metoder för anpassning och akut hantering av variation i nederbörd studerades genom intervjuer i grupp och individuellt. Betydelsen av träd- och djurtäthet för ekosystemtjänster och bönders prioriteringar analyserades på 20 gårdar. Dessutom utvärderades effekterna av Kenya Agricultural Carbon Project när det gäller användningen av mer hållbara jordbruksmetoder, storleken på majsskördar, självförsörjandegraden av mat samt besparingar.

Bönderna var medvetna om både lokala klimatförändringar och metoder för anpassning, men användningen av metoderna begränsades av avsaknad av kapital, kunskap och arbetskraft. Män hade högre utbildning, bättre tillgång till rådgivning och mer tid för sociala nätverk, och använde fler metoder än kvinnor, speciellt lågutbildade kvinnor. Regelbunden rådgivning ledde till en högre användning av mer effektiva metoder. Majsskörden var högre där bönderna hade anlagt terrasser och med träd på gården (agroforestry). Högre träddensitet ökade arbetsbelastningen men också andelen inkomster från gården, och träd var viktiga för kulturella ekosystemtjänster.

Studien visar att bönder inte kommer använda mer hållbara jordbruksmetoder så länge de inte har tillräckligt med arbetskraft, mark och kapital, samt kunskap om att fördelarna överväger nackdelarna. Därför föreslås en satsning på holistisk och inkluderande rådgivning med fokus på lågutbildade kvinnor som främjar användningen av metoder med positiva samspel, diversifierade jordbrukssystem och fokuserar på de faktorer som begränsar implementeringen av hållbara metoder. Detta stärker bönder i att bättre balansera anpassning, produktivitet och andra ekosystemtjänster för en hållbar försörjning.

Nyckelord: agroforestry, arbetskraft, gårdsstorlek, jordbrukssystem, Kisumu, kunskap, kön, skötsel, Trans Nzoia

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Preface

It is not always easy to understand the reasons behind what people do, in agriculture or in everyday life. It is especially interesting to look more closely at this in terms of farm management among smallholders in sub-Saharan Africa, where agriculture is believed to have much untapped potential. As a farmer it is necessary, but not always easy, to pursue short-term goals and maintain long-term sustainability when deciding different management strategies.

In the research described in this thesis, I focused on potential differences among smallholders in terms of access to regular agricultural advisory services, gender and biophysical setting. I looked at changes in management related to rainfall variability, ecosystem service effects in relation to more or less diversified farming systems and effects on farm management and crop yield for farmers participating in a carbon project. I also interviewed farmers, in groups and individually, in order to understand where they get knowledge and inspiration, and factors restricting them from using some desirable management practices.

The overall aim of the work was to identify how smallholders in Kenya manage their farming systems in order to adapt to rainfall variability and improve productivity, while at the same time maintaining delivery of multiple ecosystem services in a sustainable way. This thesis is just one of many efforts to understand drivers, advantages and drawbacks of different management options. No two farmers are the same and each farmer has their own reasons for their farm management choices.

Dedication

To all smallholder farmers, please close the loop and continue.

It is crystal clear from up here that everything is finite on this little blue marble in a black space, and there is no planet B.

Astronaut Alexander Gerst, from the International Space Station

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Nyberg, Y.*, Jonsson, M., Laszlo Ambjörnsson, E., Wetterlind, J., Öborn, I. (2020). Smallholders' awareness of adaptation and coping measures to deal with rainfall variability in Western Kenya. *Agroecology and Sustainable Food Systems*, DOI: 10.1080/21683565.2020.1782305

II Nyberg, Y.*, Wetterlind, J., Jonsson, M., Öborn, I. Factors affecting smallholder uptake of adaptation and coping measures to deal with rainfall variability. (Submitted to *International Journal of Agricultural Sustainability*)

III Nyberg, Y.*, Wetterlind, J., Jonsson, M., Öborn, I. (2020). The role of trees and livestock in ecosystem service provision and farm priorities on smallholder farms in the Rift Valley, Kenya. *Agricultural Systems,* vol.181, 102815.

IV Nyberg, Y.*, Musee, C., Wachiye, E., Jonsson, M., Wetterlind, J., Öborn, I. Effects of the Kenya Agricultural Carbon Project (KACP) on smallholder farm productivity and livelihoods. (manuscript)

Papers I and III are reproduced with the permission of the publishers.

* Corresponding author

The contribution of Ylva Nyberg to the papers included in this thesis was as follows:

I Planned the study together with one co-author. Collected the data. Wrote the manuscript with guidance from all co-authors.

II Planned the study together with the senior author. Collected and analysed the data. Wrote the manuscript with guidance from all co-authors.

III Planned the study together with two of the co-authors. Selected the farms, collected the majority of the data and carried out the data analyses. Wrote the manuscript with guidance from all co-authors.

IV Participated in planning the study with three of the co-authors, analysed the data and wrote the manuscript with guidance from all co-authors.

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Abbreviations

AIC	Akaike Information Criterion
C/N	Carbon/Nitrogen ratio
Ca	Calcium
GDP	Gross Domestic Product
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
KACP	Kenya Agriculture Carbon Project
KES	Kenya Shillings
MEA	Millennium Ecosystem Assessment
Mg	Magnesium
N	Nitrogen
NGO	Non-governmental Organisation
P	Phosphorus
PRA	Participatory Rural Appraisal
SDG	Sustainable Development Goal
SOC	Soil Organic Carbon
TLU	Tropical Livestock Unit
UN	United Nations
VSLA	Village Saving and Loan Association

1 Introduction

World agriculture is currently in a vicious circle of both contributing to global environmental change (Godfray & Garnett, 2014; Foley *et al.*, 2005) and being severely affected by it (IPCC, 2014). In other words, there is an urgent need to transform farming systems from primarily focusing on productivity to instead having a core of sustainability in their development (Rockström *et al.*, 2017). Sustainable agriculture is essential, rather than optional (Godfray & Garnett, 2014). In this thesis, sustainable agriculture is defined in line with the Brundtland report on sustainable development (Brundtland *et al.*, 1987): "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This includes agricultural production that does not exceed any of the planetary boundaries (Rockström *et al.*, 2009b).

In the process of transforming food production systems, research within both social and natural sciences must be combined to take a holistic approach to farming systems, in order to understand them properly (Singh *et al.*, 2016; Godfray & Garnett, 2014). Those most vulnerable to global environmental changes, *e.g.* increased climate variability, are smallholder farmers in low-income countries (Winsemius *et al.*, 2015; Maskrey *et al.*, 2007). In particular, there are large food deficits and water scarcity challenges in countries in sub-Saharan Africa (Anim & Ofori-Asenso, 2020; Rockström *et al.*, 2003). Among these countries, Kenya has relatively high potential of responding to the current challenges (Government, 2013; Rockström *et al.*, 2009a). However, the majority of smallholders in Kenya have not actively chosen to be farmers, but simply do farming since they have no 'job' (Mwaura, 2017). The available landholdings are small and decreasing in size (Jayne *et al.*, 2016; Muyanga & Jayne, 2014). With low access to advisory services and little capital, the inputs to the systems are small and nutrient cycling is often insufficient to maintain high crop yields (Deressa *et al.*, 2009; Sanchez & Leakey, 1997). This leads to unsustainable practices that risk further degrading soils in the region (Lal, 2006). In addition, smallholders are challenged by rainfall variability, which can be high in this region (Ndehedehe *et al.*, 2018).

It has been shown that relatively small changes in farming systems can improve the resilience of smallholders to climate change (Claessens *et al.*, 2012). More sustainable management practices, affecting soil health, have been identified (*e.g.* agroforestry and conservation agriculture) and have shown positive results on resilience in several research studies (Xiong *et al.*, 2018; Kiboi *et al.*, 2017; Kuyah *et al.*, 2016). However, the methods are not widely adopted, for reasons such as risky investment, poverty, land tenure rights, increased demand for labour when practising agroforestry and risk of higher weed pressure as a result of conservation agriculture (Jerneck & Olsson, 2013; Baudron *et al.*, 2012; Mercer, 2004). Change towards improved sustainability is therefore slow, and there is need for a deeper understanding of factors influencing such change (Piedra-Muñoz *et al.*, 2016; Nkonya *et al.*, 2015). The challenge is to increase productivity in the farming system in sustainable ways, using the most cost-effective sustainable methods and components that create most synergies in the system. More diversified farming systems combining crops with *e.g.* livestock and trees spread the risk, but also compete for land resources. Only a few studies have identified and compared the roles of trees and livestock for ecosystem services and farm priorities within smallholder systems (Kuyah *et al.*, 2016; Benayas *et al.*, 2009; Feld *et al.*, 2009). In particular, there is a lack of research on cultural services within agroecosystems (Kuyah *et al.*, 2016; Daniel *et al.*, 2012), although trees are known to be a possible indicator for several cultural services (Hernández-Morcillo *et al.*, 2013; Jim, 2006). Research gaps have also been identified in identification of specific agroforestry practices with positive effects on yields, improved adaptation to climate change and addressing social barriers (Mbow *et al.*, 2014b).

Lack of advisory services and factors such as poverty and gender norms are often seen as obstacles to adoption of agroforestry (Jerneck & Olsson, 2013; Kiptot & Franzel, 2012). Perceptions, knowledge and characteristics of innovations are known to restrict uptake of conservation agriculture (Droppelmann *et al.*, 2017; Baudron *et al.*, 2012). When assessing uptake of new agricultural technologies, it is thus necessary to consider farmers' characteristics, external environment and access to advisory services, as well as factors such as knowledge, perceptions and attitudes, together with the innovation itself (Liu *et al.*, 2018; Meijer *et al.*, 2015). Therefore, more research on farmers' preferences for practices is needed (Liu *et al.*, 2018).

There is also a strong need for a larger-scale and more complex approach to agricultural research, where productivity outcomes are not separated from livelihood, sustainability and ecosystem resilience (Bryan *et al.*, 2017).

Objectives

1.1 Overall aim

The overall aim of this thesis was to assess how smallholders in Kenya manage their farming systems in order to adapt to rainfall variability and improve productivity, while at the same time maintaining delivery of multiple ecosystem services in a sustainable way.

1.2 Specific objectives

1. To assess Kenyan farmers' awareness and use of adaptation and coping measures to rainfall variability, the effectiveness of the measures, limiting factors and learning sources on these measures, and to relate this awareness and use to access to regular advisory services, gender and biophysical setting (Papers I and II).
2. To determine whether more or less diversified farming systems, in terms of tree and livestock density, have an impact on delivery of ecosystem services and smallholder farm priorities (Paper III).
3. To assess the effects of the Kenya Agricultural Carbon Project (KACP) on farm productivity and livelihoods during the initial four years, using uptake of sustainable measures, maize yield, food self-sufficiency and savings as indicators (Paper IV).

1.3 Research questions

- Do access to advisory services, gender and biophysical setting affect awareness and use of adaptation and coping measures among smallholder farmers? (Papers I and II)
- Which management measures are used by smallholder farmers, to what extent and why/why not? (Papers I, II and IV)
- Which management measures affect maize yield or are perceived by smallholder farmers to be more or less effective in adaptation/coping with rainfall variability? (Papers I, II and IV)
- How does tree and livestock density on smallholder farms affect different ecosystem services and farm priorities? (Paper III)
- How does farm management, including tree and livestock density, affect smallholder livelihood aspects such as food self-sufficiency and ability to save money? (Papers III and IV)

2 Background

2.1 Smallholder farming in a changing climate

Rainfed agriculture is responsible for more than half of all global food production (Bruinsma, 2003). For smallholders, rainfed agriculture is often the only viable option. When discussing climate change and variability related to smallholder farmers, rainfall and temperature are most often the factors considered (Maddison, 2007). Overall, the long-term trends show increasing temperatures in East Africa, with decreasing rainfall in eastern parts and increasing rainfall in western parts during the long rains (Gebrechorkos *et al.*, 2019). Moreover, East Africa is predicted to experience both a temperature increase of 3.2°C (range 1.8-4.3°C) and a rainfall increase of 7% (range -3 to +25%) during the period 1980-2090 (Baede *et al.*, 2007). As a consequence of higher temperatures, total staple food production in Kenya is predicted to decrease, because of higher evapotranspiration (Herrero *et al.*, 2010). Climate data between 1962 and 2001 for Western Kenya show an annual rainfall increase of on average 2.3 mm, especially in the Highlands (Githui *et al.*, 2009). Smallholders are concerned about water availability, which is affected by both rainfall and temperature (Ochieng *et al.*, 2016). However, a change in mean annual rainfall will have different effects on agriculture depending on whether it is accompanied by a change in rainfall variability. Changes in average annual quantity of rainfall often play a smaller role than changes in variability (Thornton *et al.*, 2014). In parts of Africa, there are signs of increasing unpredictability in rainfall and expected higher variability in future (Ayanlade *et al.*, 2018). Variability in rainfall is multi-dimensional and affects smallholders' everyday life in terms of space, time, intensity and frequency (Fauchereau *et al.*, 2003). Data from Western Kenya show a decreasing trend in rainfall amounts during the long rainy season (March-May) and an increasing trend during the short rainy season (October-December) (Gebrechorkos *et al.*, 2020; Sagero *et al.*, 2018; Wetende *et al.*, 2018). This will probably affect agriculture negatively, since the long rainy season is the more reliable of the two seasons (Gebrechorkos *et al.*, 2020). More severe and frequent droughts have also been reported in Kenya (Linke *et al.*, 2020).

A change in climate pattern is just one of many parameters affecting the vulnerability of smallholder farmers. Depending on the type of climate impact and its time scale, farmers can in some cases manage adaptation by themselves (*e.g.* by changing date of planting or using soil and water conservation techniques). However, with climate change impacts on a longer time scale, it may be necessary to modify the whole farming system (Ramirez-Villegas & Khoury, 2013). This can be done through systematic change using *e.g.* new crop types or new techniques for tillage or by optimising water use, for which farmers will need expert assistance. If the climate impact is severe and seasonal crops are no longer a viable option, changing to a different land use or livelihood system will need to take place (*e.g.* obtaining off-farm income sources, selling land or migrating) and could be facilitated by government measures (Ramirez-Villegas & Khoury, 2013). When defining these types of actions, a distinction can be made between adaptation and coping measures. Adaptation to climate change is defined by the International Panel on Climate Change (IPCC) as "initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects" (Baede *et al.*, 2007). Coping, according to Sijtsma *et al.* (2013), is a short-term, non-continuous and survival-oriented solution used due to lack of alternatives. Adaptation therefore involves planning whereas coping mechanisms are often stimulated by a crisis and often lead to degradation of the resource base (Dazé *et al.*, 2009).

Through improved adaptation, a farming system can become more resilient. A more resilient farming system is robust in terms of *e.g.* absorbing climate shocks while still maintaining its functions (Rockström, 2003). Broad ecosystem-based approaches are recommended in order to buffer against negative impacts, while also being cost-effective and widely applicable (Jones *et al.*, 2012). Such approaches should consider the United Nations (UN) Sustainable Development Goals (SDGs) for 2030, a number of which are directly linked to food security (UN, 2015). For example, no poverty (SDG1), zero hunger (SDG2), good health and well-being (SDG3), gender equality (SDG5), clean water and sanitation (SDG6), decent work and economic growth (SDG8), responsible consumption and production (SDG12), climate action (SDG13), life below water (SDG14) and life on land (SDG15) are all directly or indirectly related to this complex challenge in different ways. The SDGs clearly show how different aspects of sustainable development are interrelated (UN, 2015).

The rural poor in a low-income country, *e.g.* Kenya, are most directly dependent on ecosystem services and are thus most vulnerable to changes in the ecosystem. Smallholders' ability to adapt to or cope with changes are also affected by other multi-scale stressors within their current natural resource and socio-economic situation (Singh *et al.*, 2016). To reduce the risk of food insecurity both currently and in the future, these farmers need to enhance their resilience by using more sustainable and resilient agricultural practices. Several approaches, such as climate-smart agriculture (Lipper *et al.*, 2014), and sustainable intensification have been developed to deal with these challenges (Wezel *et al.*, 2015). Climate-smart agriculture is defined as agriculture that "sustainably increases productivity, enhances resilience, reduces/removes greenhouse gas emissions, and enhances the achievement of national food security and development goals" (Palombi & Sessa, 2017). Sustainable intensification is an approach that includes ecological, economic and social aspects (Öborn *et al.*, 2017a; Pretty *et al.*, 2011). Despite some debate regarding the definition of sustainable intensification (Wezel *et al.*, 2015), it is obvious that farming systems have to become both sustainable and more resilient. The current concepts can create a platform (Campbell *et al.*, 2014), from where different sustainable management measures can develop and spread.

2.1.1 Ecosystem services

Climate change and variability are challenges to smallholders in their agriculture. Nutrient cycling and availability and biodiversity below and above ground are other challenges that are high on the research agenda (IPCC, 2018; Crist *et al.*, 2017; Smith *et al.*, 2017; Wall *et al.*, 2015; Wu & Ma, 2015; Rockström *et al.*, 2010). To understand the situation of smallholder farmers, it is important to understand the larger ecosystem and its services. Ecosystems are dynamic, complex systems of plant, animal and microorganism communities and the non-living environment, interacting as a functional unit (MA, 2005). According to the Millennium Ecosystem Assessment (MEA) framework (MA, 2005), ecosystem services are the benefits people obtain from ecosystems, such as supporting, regulating, provisioning and cultural services. The MEA framework is applied in this thesis, although there are other ways of considering system interrelations (Mace *et al.*, 2012).

The fundamental ties humans have to nature are becoming increasingly invisible to many people (Viking Abrahamsson *et al.*, 2001). Ecosystem services have become a popular way of commodifying nature. Researchers using the framework have identified challenges in measuring ecosystem services (Reyers *et al.*, 2013) and have developed approaches to assist in method selection (Harrison *et al.*, 2018). The ecosystem services concept is a good way to explain the links between ecosystem functions and processes leading to benefits to humans, but it is difficult to put values on ecosystem services. Some researchers have tried to estimate values through selecting certain indicators for functions or processes and estimating their values, or estimating what it would cost to replace them without a functioning ecosystem (Wang *et al.*, 2016; Spangenberg & Settele, 2010; Constanza *et al.*, 1997). For quantification, it is desirable to use several relevant indicators chosen for the local context and linked to the final services (Manning *et al.*, 2018; Egoh *et al.*, 2012). Studies on cultural ecosystem services are rare and research gaps have also been found regarding ecosystem services on farm and landscape level in agriculture, where a majority of the benefits are found (Kuyah *et al.*, 2016).

2.1.2 Diversification of farming systems and agroforestry

Diversifying farming systems has long been an insurance strategy among smallholders (Kahane *et al.*, 2013). Besides improved capacity to buffer against disturbances, a system converting from few to many productive crop, tree and livestock species can also gain significantly in terms of ecosystem services, according to *e.g.* Naeem and Li (1997), Lin *et al.* (2008) and Kearney *et al.* (2017). Higher diversity often means better and more reliable functioning of ecosystem services (Isbell *et al.*, 2011; Benayas *et al.*, 2009; MA, 2005), although this is not always the case (Bullock *et al.*, 2011; Carpenter *et al.*, 2009). More focus is needed on practices creating sustainable synergies in agriculture. Synergies create win-win options in agriculture (Lal, 2004). One system that has attracted much attention in terms of both adaptation and mitigation benefits is agroforestry (De Giusti *et al.*, 2019; Droppelmann *et al.*, 2017; MA, 2005). The Millennium Ecosystem Assessment synthesis (MA, 2005) suggest that agroforestry is one of only a few systems that can meet food and fuel demands, while at the same time restoring soils and contributing to biodiversity conservation.

Agroforestry is defined in this thesis as a planned agro-ecological system of trees/shrubs growing on the same land as food crops, fodder and/or animals, interchanged in time or space, in order to exploit the components and their interactions. Agroforestry has been described as a multi-functional production system that has potential to help small-scale farmers improve their food security, adapt to climate variability and mitigate climate impacts (Abbas *et al.*, 2017; Mbow *et al.*, 2014a; Verchot *et al.*, 2007; MA, 2005). Conversion from crop-based (mainly maize-beans) small-scale agriculture in East Africa to agroforestry practices often results in both intensification and diversification of farm production, two smallholder strategies commonly used to improve food security and financial security (Jhariya *et al.*, 2019; Sinclair *et al.*, 2017). Diversification, both within the farm and outside, makes farmers less vulnerable to climate stresses such as floods or droughts (Quandt *et al.*, 2019). However, the labour requirements may change, *e.g.* inclusion of trees has been shown to result in higher or lower workload (Dewees, 1991; Hoekstra, 1987).

Smallholder uptake of new technologies is a process, where a few adopt initially, more after evaluating the first adopters, and some seldom or never (Mercer, 2004). Human behaviours and especially habits are difficult to change, which might be a greater obstacle than assumed by many researchers (Klöckner & Verplanken, 2018). Poor farmers are less likely to try new farming practices (like agroforestry) due to perceived risks (Mutoko *et al.*, 2014; Scherr, 1995). There is a clear trade-off between the money or labour that farmers invest in a practice and the added benefit it brings. For trees and agroforestry, it is important not to focus solely on field-level research, since the majority of benefits can be expected on farm level (Kuyah *et al.*, 2016). Therefore, it is important to look for economic incentives for both establishing and managing agroforestry (Scherr, 1995)

2.2 Farming in Kenya

More than 70% of the population in sub-Saharan Africa are subsistence farmers practising rain-fed agriculture and the majority of them live in poverty and are highly vulnerable to climate stresses (Mann *et al.*, 2009; WHO, 2000). However, farmers in the region have long been adapting to both short-term variations and long-term trends in rainfall in their farming environment (Challinor *et al.*, 2007; Meinke & Stone, 2005).

Kenya is a fast-developing country in East Africa and therefore has great potential to take the lead in reaching the Paris Agreement goals on climate change mitigation (Agreement, 2015). Kenya's first action in this regard was the National Climate Change Action Plan 2013-2017 (Government, 2013). The latest version of the plan covers the period 2018-2022 (Government, 2018) and sets goals for agriculture and for other sectors such as forestry, transportation and industry. More than 70% of the rural population in Kenya rely on agriculture for their employment and more than a quarter of gross domestic product (GDP) is derived from agriculture (Government, 2018). The three main mitigation actions proposed for climate change are: limited burning in cropland management; more use of conservation tillage; and agroforestry as part of climate-smart agriculture (Government, 2018).

Compared with other countries in the region, Kenya has good potential for coping with rainfall variability through using low-cost measures to improve utilisation of its relatively high rainfall amounts in achieving higher productivity in agriculture (Rockström *et al.*, 2009a). Unfortunately, monitoring to assess the effects of rainfall variability and preparedness work to improve the future adaptive capacity of farmers have been low on the political agenda, and therefore not prioritised within agricultural extension services (Lal, 2015; van Aalst *et al.*, 2008; Shisanya & Khayesi, 2007).

2.2.1 To be or not to be…a farmer

Subsistence farmers with small landholdings (<2 ha) and using mainly manual labour are common in sub-Saharan Africa (Lal, 2015). Farming in Kenya has long been associated with low productivity and unattractiveness to young people and is regarded as a stop-gap until a better opportunity arises (Mwaura, 2017). Basically, farming is the default if no other option is available.

The global population growth rate is expected to decline eventually, but the world population is still expected to increase by another 2 billion people by 2050 (UN, 2019). During the same period, the population in sub-Saharan Africa is predicted to double (UN, 2019). The population growth rate was 2.3% for Kenya in 2018 (WB, 2019). This population increase will continue to put high pressure on food security in its full definition (FAO, 2008). There has to be an increase in production through sustainable intensification, in Kenya and elsewhere, combined with a shift from unhealthy consumption and food waste to more climate-smart diets in other parts of the world (Campbell *et al.*, 2014).

Globally, the area of agricultural cropland per capita has declined from 0.45 ha to 0.22 ha in the past 50 years (Bruinsma, 2003). Population growth is one of the reasons for this decline. In sub-Saharan Africa, land holdings are subdivided from parents to children (often from fathers to sons), into smaller and smaller pieces (Kwame *et al.*, 2019). However, when the agricultural plots are too small to sustain a family, the subdivision has to stop and young people have to look for other ways to sustain themselves. Some African countries (*e.g.* Ghana, Tanzania and Zambia) have a rapidly increasing trend for medium-scale farms (5-100 ha), but in Kenya only the number of small-scale farms (0-5 ha) is increasing (Jayne *et al.*, 2016). The smaller the landholding, the more vulnerable the farmer. Assessing the vulnerability status of smallholders requires a broad, multi-dimensional approach, where prioritisation and management of trade-offs are better understood and where climate and non-climate stressors are considered (Williams *et al.*, 2018).

2.2.2 Prioritisations by farmers

To manage trade-offs, smallholders have to make short-term and long-term prioritisations every day, based on their complex realities (Kebede *et al.*, 2019). Examples of priorities include what to produce, inputs to use in terms of labour and nutrients, the aim of the production and the risks farmers are willing to take. Farmers have to consider their own abilities, their land, neighbours, climate and other available resources (Figure 1). Many smallholder farmers have limited incomes and minimal ability to accumulate enough money for investments in soil fertility (Stephens *et al.*, 2012). Even trade-offs regarding crop residues often do not favour soil fertility (Castellanos-Navarrete *et al.*, 2015; Tittonell *et al.*, 2015), since they are often used as fodder or fuel (Nduwamungu & Munyanziza, 2012). Rainfall variability, with *e.g.* a prolonged dry season, further increases competition for available biomass (Rufino *et al.*, 2011).

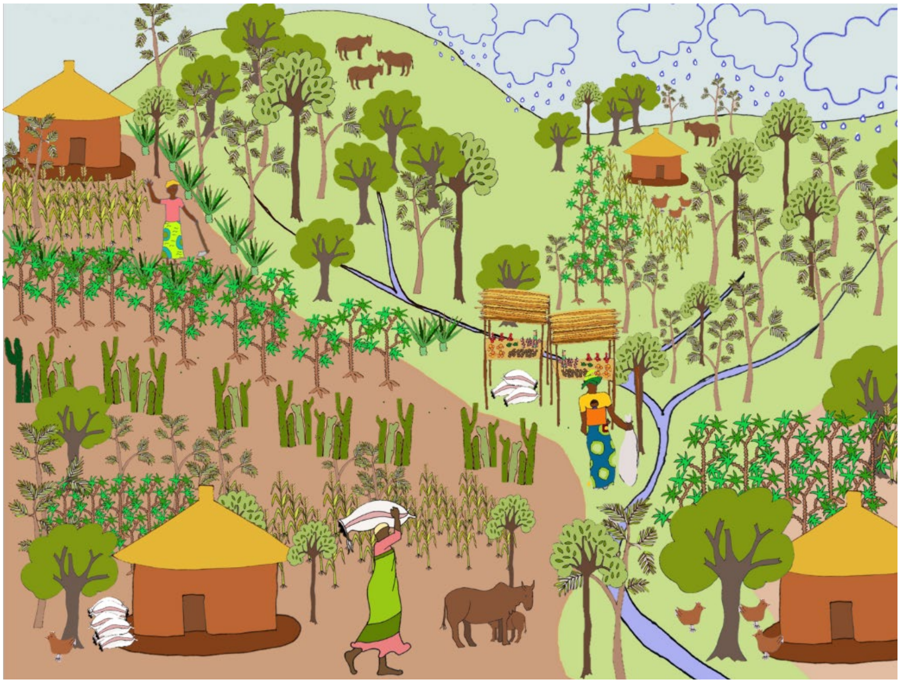

Figure 1. Illustration of a farming landscape with different factors that smallholders need to have in mind when planning their production, such as crops, livestock and trees, their own skills and available labour, land and water resources, climate, market opportunities and interactions with neighbours.

Labour and land are examples of resources that can drive farm management towards a more complex farming system providing most of what the household needs, but taking more labour, or towards a simpler system that can be combined with off-farm work and income, since it requires less labour (Dahlin & Rusinamhodzi, 2019; Muyanga & Jayne, 2014). Off-farm opportunities are seen as both a necessary shift for smallholders and a threat to more sustainable agriculture (Xie *et al.*, 2018). One option for potentially reducing on-farm labour and contributing to increased sustainability is greater use of perennial crops among smallholders in the tropics (Dixon & Garrity, 2018) and on large-scale farms in Europe (Marquardt *et al.*, 2016). Inclusion of different farm components, such as perennial crops or trees, is generally recommended in order to achieve more sustainable and robust production (Nguyen, 2017; Kahane *et al.*, 2013), although knowledge of successful multi-component systems is often lacking (Englund *et al.*, 2020).

2.2.3 Advisory services

Knowledge on how best to prioritise and manage production by adopting more sustainable practices can be obtained through education or advisory services, where the latter can play an important role in communities with low education levels (Abdulai & Huffman, 2014). How the agricultural extension and advisory services provided by public (governmental) and private extension agents can complement each other is regularly assessed (Mwololo *et al.*, 2019; Kidd *et al.*, 2000). Government agencies often lack funding and are thus less efficient than private actors, but private actors often target better-off households that can pay for their services (Mwololo *et al.*, 2019). The challenge is therefore often how to target resource-poorer households (Mwololo *et al.*, 2019; Kidd *et al.*, 2000). Non-governmental organisations (NGOs) are private but not for profit, and provide free services and cover larger areas than purely private actors. A limitation with NGOs is the relatively short-term, project-based funding (Muyanga & Jayne, 2008).

Apart from different external sources, farmers commonly also learn horizontally from each other. Neighbours learn from talking and visiting each other or more formally through selected farmer trainers, which have been shown to be effective (Kiptot & Franzel, 2019). The benefits of farmer trainers are that they are locally available, cost-effective and often remain in the village even after the contracted period (Lukuyu *et al.*, 2012). However, farmer trainers often focus on disseminating a few technologies to many households (Lukuyu *et al.*, 2012) and therefore do not play the same role as advisors, who can be expected to have a portfolio of technologies and new ideas, enabling farmer-specific advice. For many households, social learning through farmer trainers is more powerful for adoption rates of a technology than learning from external agricultural extension services (Krishnan & Patnam, 2014). However, even with access to external or horizontal learning sources, there are still many obstacles, including education, labour, capital and social networks, to implementation of new technologies that can help farmers *e.g.* adapt to climate change or improve soil fertility (Descheemaeker *et al.*, 2016; Abdulai & Huffman, 2014).

2.2.4 Land degradation and ways of rehabilitation

Agricultural landscapes are increasingly being degraded and, to restore their functions, large-scale investments in rehabilitation are needed (Lohbeck *et al.*, 2018; Mulinge *et al.*, 2016). Degradation of Kenyan soils, in terms of *e.g.* soil erosion, soil nutrient depletion and agro-biodiversity loss, is estimated to cost four times as much in reduced crop and livestock production as the necessary investment in land rehabilitation, calculated over a period of 30 years (Mulinge *et al.*, 2016).

Degraded soils can be restored *e.g.* through avoiding bare soil, removing invasive species, promoting higher functional diversity and growing trees together with annual crops on farms (Lohbeck *et al.*, 2018). Species diversity, with *e.g.* different rooting and canopy characteristics, enables more efficient use of available resources, both above and below ground (Reijntjes *et al.*, 1992). Having sufficient trees in a landscape can improve the water infiltration capacity, leading to reduced run-off and soil erosion (Nyberg *et al.*, 2011). Shade trees can directly influence soil temperature, soil moisture and organic matter composition and, together with soil properties, affect the decomposition and accumulation rates of soil organic matter in the topsoil (van Noordwijk *et al.*, 2015).

Soil organic matter added through *e.g.* manure is especially effective in improving soil physical properties such as water-holding capacity in highly weathered soils (Vitousek *et al.*, 2009). It stabilises the soil structure by providing a mix of fine and coarse pores and lowers the bulk density (Young, 1997). Soil organic matter further adds humus, food for soil fauna, which improves the biological activity and also enhances the cation exchange capacity, making nutrients more available to plants (Vitousek *et al.*, 2009; Young, 1997). Soil composition and structure thereby have a major influence on soil fertility and provisioning services.

Soil organic matter content can be boosted through adding manure or through including trees on farms for higher functional diversity. Trees have the potential to maintain crop yields while adding organic matter, avoiding bare soil and producing wood and non-timber forest products (Lohbeck *et al.*, 2018). Positive effects from added mulch on erosion control and water regulation are evident already in the first three years after conversion to agroforestry practices from conventional crop farming (Kearney *et al.*, 2017). To boost farming systems further, inorganic fertilisers in combination with organic amendments could probably help to reach a new equilibrium in soil organic carbon levels. Relatively small amounts of fertiliser could make a significant difference, especially if used in combination with manure (Vanlauwe *et al.*, 2010). However, not all smallholders can afford inorganic fertilisers and lower income has been found to lead to less investment in soil (Iiyama *et al.*, 2008).

2.2.5 Gender and social aspects

Many previous studies have examined uptake of more sustainable land management measures, such as mulching, agroforestry practices, planting of cover crops and reduced tillage. These studies have often found that uptake of what scientists perceive as sustainable land management measures is surprisingly low, even though benefits are expected (Jambo *et al.*, 2019; Nigussie *et al.*, 2017). Apart from the characteristics of the technology itself, land, labour and gender seem to affect the uptake (Nigussie *et al.*, 2017). Lack of capital is another important factor that can lead to more unsustainable practices and thereby reduced food production (Abdulai & Huffman, 2014). Food insecurity has been found to be strongly associated with low education levels, low social capital, weak social networks, low income and unemployment (Smith *et al.*, 2017). These factors can also increase smallholder vulnerability to climate stress (Pandey *et al.*, 2015). Individual vulnerability depends on a farmer's exposure to climate stresses, the risks they need to take, how sensitive they are to those stresses in terms of availability of farm inputs, labour, capital etc., and their personal adaptive capacity, where knowledge and culture play important roles (Furlow *et al.*, 2011; Adger *et al.*, 2009).

Gender is another important aspect to consider in relation to lack of uptake of more sustainable measures. Traditionally, women in sub-Saharan Africa are responsible for the home and the children, while men are responsible for income generation (Kiptot & Franzel, 2012; Laszlo Ambjörnsson, 2011). The responsibilities of men and women in terms of farm work also differ. Men are responsible for cash crops, large livestock, long-term trees and land, while women are responsible for food crops and small livestock such as poultry (Manzanera-Ruiz *et al.*, 2016). Human resources in terms of knowledge and information may also differ between male and female farmers. Compared with men, women in sub-Saharan Africa have less access to productive resources, extension and advisory services, and networks and decision making bodies within the community (Farnworth & Colverson, 2015). Female-headed households are the most vulnerable (Flatø *et al.*, 2017). Even within the household, women often have less decision-making power, have a lower level of education and are less able to attend meetings and information gatherings due to their responsibilities in terms of food and children (Nyasimi & Huyer, 2017; Farnworth & Colverson, 2015). Several studies have shown that programmes considering gendered constraints, responsibilities and resources are more likely to succeed in improving production (Doss, 2018; Crist *et al.*, 2017). Empowering women through extension services has also been found to increase productivity and reduce poverty in Western Kenya (Diiro *et al.*, 2018).

3 Materials and methods

This chapter provides an overview of the work described in Papers I-IV (Figure 2). For full details of the materials and methods used in all studies, see the individual papers.

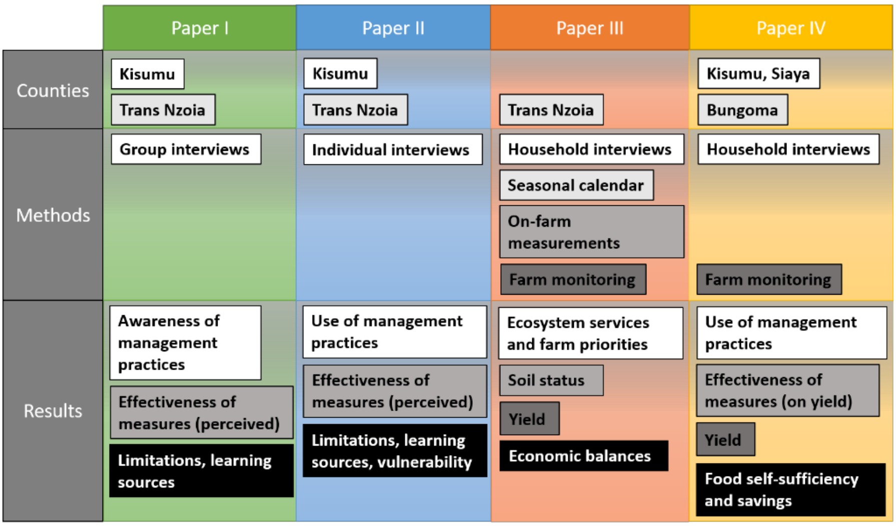

Figure 2. Overview of the work performed in Papers I-IV, the study areas (counties), methods used and types of results obtained.

3.1 Study areas

The study was carried out in Western Kenya (Figure 3). Different areas within two contrasting biophysical settings were compared in Papers I, II and IV, while Paper III focused only on one of these areas. The studies covered a gradient from Lake Victoria (Kisumu County) to higher areas in the Rift Valley (Trans Nzoia County).

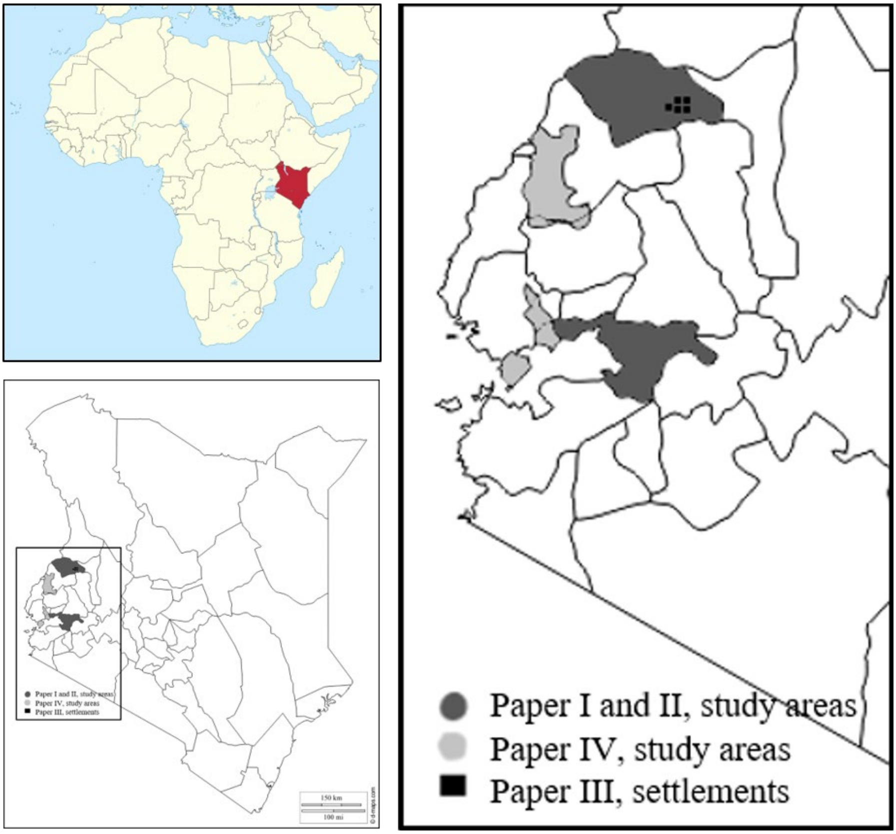

Figure 3. Map of Kenya showing the study areas in two agro-ecological zones in the western part of the country. The coordinates for the total area, including all study sites are 0°41’80.48”S 34°24’61.44”E and 1°29’36.11”N 35°35’68.54”E. Papers I and II were carried out in Kisumu (southern) and Trans Nzoia (northern) counties, Paper III in five villages (settlements) in Trans Nzoia county and Paper IV in Kisumu and Siaya counties (southern part, called Kisumu) and Bungoma county (northern part, called Bungoma).

Kisumu, at altitude ~1100 m asl on the shores of Lake Victoria, has relatively warm temperatures, flat topography (Figure 4) and soils (Vertisols and Planosols) that are prone to flooding (Jaetzold *et al.*, 1983). Kisumu County covers an area of around 2086 km^2 and is characterised by proximity to Kisumu town, with job opportunities, and Lake Victoria, with a long tradition of fishing communities. Kisumu County has mean annual rainfall of 1362 mm and mean minimum and maximum temperature of 17 and 30°C, respectively (data from Kisumu meteorological station).

Figure 4. Typical Kisumu landscape with flat land and relatively few trees. Free-grazing livestock keep the grass short and live fences are sporadic.

Trans Nzoia, located farther north in the Rift Valley, is larger than Kisumu County (2496 km^2) and has more favourable soils, mainly Ferralsols (Government, 1985) and more undulating topography (Figure 5). It also has a cooler climate due to higher altitude (~1800-2000 m asl), as it is near Mt Elgon. Mean annual rainfall in Trans Nzoia is 1267 mm and mean annual minimum and maximum temperature is 12 and 26°C, respectively (data from Kitale meteorological station). Within the study areas, the inter-annual variability in rainfall is large, with total annual precipitation ranging between 919 and 1829 mm in Trans Nzoia (28-year average) and between 1029 and 1791 mm in Kisumu (44-year average) (data from Kisumu and Kitale meteorological stations).

Figure 5. Typical Trans Nzoia landscape with undulating land and relatively many trees. Livestock are often kept stalled and barbed wire fences are common.

Trans Nzoia is a major production site of Kenya's staple crop, maize, and the area is known as the 'grain basket of Kenya' (Onyango, 2009). Land in Kisumu is inherited within one tribe (fishermen by tradition), whereas in Trans Nzoia large-scale colonial farms were subdivided after independence (1963) and bought by a mix of tribes specifically for farming. In the current land use, there are still large- and medium-scale farms active in Trans Nzoia and tree cover is higher than in Kisumu, with more woodlots and more trees in or around fields. Farms are largely fenced with barbed wire or wood in Trans Nzoia, while scattered plants such as *Aloe vera* or sisal (*Agave sisalana*) demarcate boundaries in Kisumu, but rarely keep livestock in or out. In Kisumu County, it is more common to see abandoned farmland than in Trans Nzoia. Maize (*Zea mays*) intercropped with common beans (*Phaseolus vulgaris*) are the most common crops in both areas, with one long maize season in Trans Nzoia (yielding more) and two seasons in Kisumu. Bananas (*Musa* spp.) are common in Trans Nzoia, and sorghum (*Sorghum bicolor*) and sugarcane (*Saccharum officinarum*) in Kisumu. In agricultural terms, Trans Nzoia is a fertile and productive area due to less evapotranspiration, caused by lower temperatures at the higher altitude. Kisumu County has more problematic cropping conditions due to the impermeable soils and to frequent floods and droughts and severe gully erosion in some parts. Livestock are normally local breeds in Kisumu (Muyekho *et al.*, 2014), while the majority of livestock are mixed with exotic breeds in Trans Nzoia (Mudavadi *et al.*, 2001). The weed striga (*Striga hermonthica*), which is a sign of low soil fertility, is also more common in Kisumu (Kanampiu *et al.*, 2018; Wetende *et al.*, 2018). In the study described in Paper IV in this thesis, Siaya and Bungoma Counties were also included. Siaya is rather similar to neighbouring Kisumu, but with slightly lower temperatures, while Bungoma is more similar to Trans Nzoia, with a higher altitude but with two distinct rainy seasons, and thus two maize seasons, as in Kisumu (Jaetzold *et al.*, 2005).

3.2 Experimental design in Papers I-IV

The work presented in this thesis was designed with the intention of gaining a deeper and broader understanding of farm management among smallholders in the study region. It consisted of four studies, described in Papers I-IV, which examined the challenges related to rainfall variability experienced by smallholder farmers in the study areas, sustainable management measures that these farmers were aware of and actually used to adapt to a challenge or develop the farm, and the effects of some of these measures on maize yield. The three main components of the farming system (crops, trees, livestock), combinations of these and their effects on several ecosystem services and farm priorities were also studied, as were the effects of farm management practices on selected livelihood aspects.

In all studies, smallholders were defined as farmers with ≤2.5 ha of land. Papers I and II, which assessed awareness and use of adaptation and coping measures, were based on interviews. Papers I and II applied a similar set-up, with two geographical areas (biophysical settings) and separate group interviews with women and men (Paper I) or equal numbers of individual female and male respondents (Paper II). Both papers also included farmers with or without access to regular agriculture advisory services during the period 2000-2010.

Paper III, which examined the effects of tree and livestock density on ecosystem services and farm priorities, had a different design whereby 20 farms were studied during one year. All farms were located within the same geographical area and were selected in a factorial design to have either high or low density of trees and high or low density of livestock, in addition to having crop production (Figure 6).

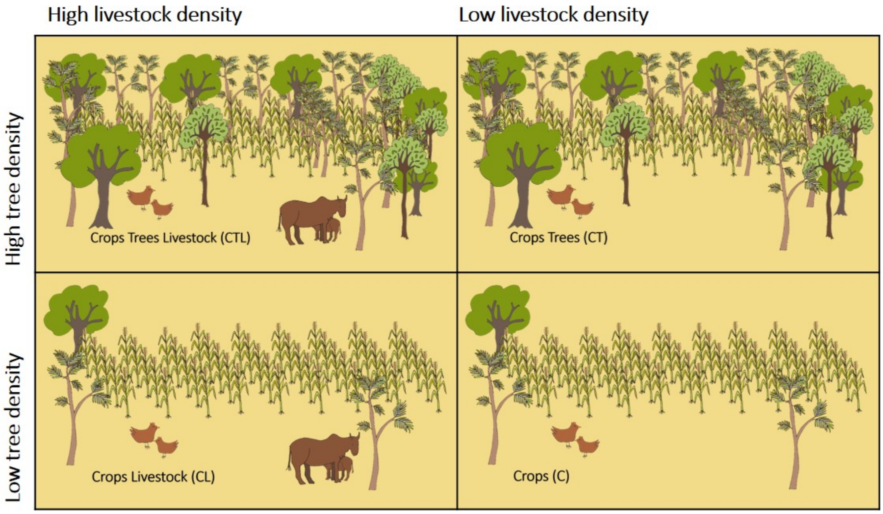

Figure 6. Smallholder farms in Kenya differ widely in tree and livestock density. This illustration represents the four cases of farms with crops and high or low tree and livestock density (represented here as farms with or without cattle), which were studied in Paper III.

Each farm type was identified in five adjacent settlements, in a block design. These five settlements (Botwa, Hututu, Sinoko, Wehoya and Yuya) were chosen to have similar soil type (mainly Ferralsols; Government, 1985), climate within the agro-ecological zone 'upper midland' (FAO, 1996), similar land use history including former large-scale maize production, and not frequently affected by flooding.

Paper IV, on use of sustainable land management practices and their possible effects on maize yield, food self-sufficiency and savings, covered two geographical areas. Data on farms that participated in the Kenya Agricultural Carbon Project (KACP) were compared with data on neighbouring control farms. The first four years of the KACP period, covering in total eight maize seasons, were included in the data analysis.

3.3 Research methods used for data collection

3.3.1 Interviews (Papers I and II)

Interviews in Paper I were carried out with groups of female and male farmers, to identify different adaptation and coping measures (Online resource 3 in Paper I). The list of adaptation and coping measures obtained as an outcome of Paper I, was complemented through 10 individual interviews with field advisors, following the same interview guide as for the group interviews. The full list of measures was then used for individual farmer interviews in Paper II in order to better understand the actual use of the measures.

Both group and individual farmer interviews were conducted in Kisumu and Trans Nzoia Counties. Interviews with male and female farmers were held separately and farmers having access to regular advisory services through an NGO called Vi Agroforestry were placed in separate interview groups from those who had no access to regular advisory services. Both group and individual interviews targeted women and men as farmers, and not necessarily as heads of households. Each interview lasted 1-3 hours and was carried out using a semi-structured interview guide (Hay, 2010) for the groups and a questionnaire for the individual interviews (based on outcomes of the group interviews). During all interviews, adaptation measures were referred to as 'measures one plans for', whereas coping measures were referred to as 'measures one may be forced to take'. This was based on the concept that coping measures are driven by short-term gains which can lead to erosion of the farming system's resilience, while adaptation measures are instead undertaken for a longer-term positive response of the farming system's resilience (Singh *et al.*, 2016).

There were 16 group interviews in total in Paper I, with three factors (women and men; access and no access to regular advisory service; two biophysical settings) and two replicates, and each group interview had between six and 12 participants, as recommended in the literature (McLafferty, 2004; Kumar, 1987).

Group interviews were recorded by a group secretary on flipcharts and by audio-recording. No formal transcription or coding was used. The interview guide had standardised questions across interviews and saturation (exhaustion) of measures was achieved according to recommendations by Hay (2010) in both counties for the group interviews.

A total of 80 individual interviews were held in Paper II, with the same three factors as for the group interviews and with 10 replicates. The individual interviews also collected information regarding characteristics of farmers' vulnerability to rainfall variability and whether the interviewees felt more or less vulnerable than their neighbours. Reasons why measures were not used and the learning sources for measures used were included in both studies. During group interviews (Paper I), learning sources and limitations were identified for each measure, while individual farmers (Paper II) mentioned general learning sources and limitations in their farming.

If a farmer had experience of using a measure during the previous three years, they were asked to score the effectiveness on a scale from 0 to 5 where "0 = no positive effect to adapt to or cope with rainfall variability; 1 = small positive effect, but never enough to adapt to or cope with rainfall variability alone; 2 = visible positive effect, but rarely enough to adapt to or cope with rainfall variability alone; 3 = visible positive effect, sometimes enough to adapt to or cope with rainfall variability alone; 4 = strong positive effect, often enough to adapt to or cope with rainfall variability alone; and 5 = enough to adapt to or cope with rainfall variability alone". Among measures used by at least 10 farmers (12.5%), a group of 22 measures with score >3.4 were identified as the most effective measures and a group of 17 measures with score <3.0 were identified as the least effective measures.

When preparing data for statistical analysis, the measures were divided into 11 categories in Paper I and 12 categories in Paper II (since one more category was added based on the responses from the field advisors), according to the nature and aim of the measures. The scale at which measures were decided upon/practised (field, farm or landscape) was also identified for all measures. Semi-structured interviews and farm monitoring carried out in Papers III and IV are described in sections 3.3.2 and 3.3.4 below.

3.3.2 Semi-structured interviews and farm monitoring (Paper III)

Indicators for ecosystem services were selected and monitored on 20 farms with high or low tree and livestock density (with or without cattle) in Paper III. Farm size and available family labour were also considered in the analyses. Previous studies have shown that ecosystem services indicators are challenging to identify, evaluate and compare (Greiner *et al.*, 2017; Egoh *et al.*, 2012), and therefore a range of indicators representing the same services were used in Paper III. Maize and common bean yields, production of firewood, fruit, eggs and milk, and total value of farm production were used as indicators for provisioning services. Supporting services, such as soil fertility, had indicators including percentage of total soil organic carbon (SOC), here assumed to be equal to total soil carbon, total soil carbon/nitrogen (C/N) ratio, plant-available (extractable) soil phosphorus (P) and potassium (K) concentrations and soil pH. Indicators for soil structure maintenance and water retention, as examples of regulating services, were represented by topsoil bulk density and water infiltration capacity. Cultural service indicators included presence of ornamental plants and proportions of different tree species on a farm used for recreation and aesthetics (shade to relax in and beauty). Since number of trees was a selection criterion for the farms, both proportions and actual numbers of trees for cultural services were considered.

Paper III also included indicators of farm priorities related to *e.g.* level of self-sufficiency versus market orientation of the farm and management and diversity of production. Indicators included the proportion of purchased food in total food consumed and the proportion of off-farm income in total income, which have also been used in previous studies (Ifejika Speranza *et al.*, 2014). In terms of farm priorities related to field and farm management, annual application of organic and inorganic amendments and the proportion of maize residues returned to the field were included as indicators, as was average man-hours spent on farm work per day. In relation to diversity, the indicators were chosen to reflect the ability of a system to spread risks (Quandt *et al.*, 2019). Therefore, the numbers of crop, animal and tree species on the farm were included as indicators.

Data collection on the 20 farms was carried out using empirical field measurements, sample collection and semi-structured interviews, in combination with the Participatory Rural Appraisal (PRA) seasonal calendar tool (Cavestro, 2003). The economic flows were followed through forms given to farmers to keep records in between the monthly visits. Crop, tree and livestock inventories were completed for each farm, in order to assess the diversities and densities.

3.3.3 Sampling and tests for soil chemical and physical analyses (Paper III)

In Paper III, the effects of tree and livestock density on supporting and regulating ecosystem services were studied using a number of soil chemical and physical indicators. Composite soil samples were taken at 0-15 cm depth from the largest maize/common bean field, the homestead, and two to four more fields on each farm, air-dried, sieved (2 mm) and used for chemical analyses carried out at the Swedish University of Agricultural Sciences. Total soil carbon and total nitrogen (N) were analysed using a carbon-nitrogen-sulphur (CNS) 2000 dry combustion analyser. Extractable P, K, magnesium (Mg) and calcium (Ca) were determined by Mehlich 3 extraction (Mehlich, 1984), followed by element analysis using atomic emission spectrometry (ICP). In addition, soil pH ($CaCl_2$) was measured and C/N ratio was calculated. All element concentrations were expressed as farm averages. Soil bulk density was determined from three dried and weighed bulk density cores collected from the Ap horizon in soil pits dug in the main maize/common bean field on each farm.

Infiltration rate was determined through six double-ring tests on a maize/common bean field on all 20 farms (Brady & Weil, 2002). Two metal rings (20 and 30 cm diameter) were pressed around 5 cm down into the soil. Water was poured into the inner ring and between the rings, to prevent water moving horizontally in the soil, and then infiltration rate was measured until the rate was stable. Mean infiltration rate per farm was used in the data analysis.

3.3.4 Data collection in the Kenya Agriculture Carbon Project (Paper IV)

The Kenya Agriculture Carbon Project started in 2009 and was implemented in two areas of Kenya, called 'Kisumu' (including Kisumu and Siaya Counties) and 'Bungoma' (including Bungoma County). The KACP methodology was developed through the NGO Vi Agroforestry, assisted by the BioCarbon Fund of the World Bank (Woelcke, 2010). KACP was a unique development project, since smallholder farmers received carbon credits for soil carbon, and not just for tree planting (Öborn *et al.*, 2017b). Farmers contracted in the project received advisory services through Vi Agroforestry, with the focus on sustainable agricultural land management practices including agroforestry, farming business and village saving and loan associations (VSLA). Monitoring to estimate carbon emissions reductions was done through follow-ups of farm management practices implemented on different fields on the project farms. Of the initial 10,873 project farms, 200 farms (100 in each project area) were selected for monitoring more closely by KACP field advisors (Lager, 2012). Selection of the 100 farms in each project area was carried out by agro-ecological zone stratification and randomisation within clusters based on a systematic grid, in order to represent the two areas in the best way possible (Seebauer *et al.*, 2010). Data from those 200 farms were analysed in Paper IV. In addition, for the purposes of this research study, a set of 160 control farms (80 in each project area) was selected in 2012, in order to assess the added values of the project (De Graaff *et al.*, 2019). When selecting those control farms, the 200 project farms were used as reference points and the second farm to the north of the project farm was selected, as long as the owner consented.

The data in Paper IV were collected by KACP staff according to their normal routines for monitoring and evaluation within the development project. In addition, they agreed to carry out similar data collection on control farms selected during the fourth project year for use in Paper IV. Farmers were provided with forms for record keeping in combination with semi-structured interviews by field staff during regular visits. The records on management and yields were also compared with reality through farm visits twice a year during the initial four years of KACP. The area of all fields and farms was estimated using Global Positioning System (GPS). By the end of the fourth year, KACP staff were collecting the same type of data from the control farms and at that time the control farmers were asked to report recalled yields from the previous years. The monitoring data included both recommended land management practices, such as i) no tillage, ii) crop residues for direct mulch, iii) raw manure composting, iv) cover crops, v) terracing and vi) water harvesting structures; and practices to be avoided due to higher carbon emissions, such as vii) removing crop residues from fields, viii) applying raw manure to fields and ix) burning residues. Records on the use of all nine practices were available for all years for project farms, but only for the fourth year for control farms. Data on number and species of trees on farms and on self-estimated food self-sufficiency and savings were collected for all farms in 2012.

3.4 Statistical analyses

All statistical analyses were conducted in R 3.4.2 (R Core Team, 2019) and are summarised in Table 1. In Paper I, generalised linear mixed-effect models were fitted to test effects of different factors on: i) the number of measures identified; ii) the average score allocated to the measures; and iii) the number of times different learning sources were mentioned. Fixed factors included area (Kisumu or Trans Nzoia), gender, regular access to advisory services or not, and type of measure (adaptation or coping). Farmer group was included as a random factor. A separate test was conducted for the scale at which a measure was deployed (field, farm or landscape).

Groups of adaptation and coping measures were analysed in Paper II, assessing their use and scores, using a linear model and full-factorial three-way analysis of variance (Anova) with gender, site and regular access to advisory services or not as fixed factors. Differences in learning sources and barriers to uptake were tested using logistic regression with gender, site and regular access to advisory services or not as explanatory variables. Interactions between explanatory variables were tested. If a variable was non-significant in a Chi-square test based on the full-factorial model, it was excluded from further analysis.

In Paper III, all ecosystem services indicators and farm priority variables were considered as response variables in statistical analyses using the lm function. The linear model was based on a fully factorial design, with high and low tree and livestock density and their interactions. Farm size (ha) and family labour (available adults were counted as one and children as half a labour unit) were added as co-variates. A factor for settlements (blocks) was added after the co-variates and before the other factors. Standardised Z-scores (equation 1) were used to compare all indicators and variables for the different farm types in radar diagrams:

$$Z = (x - \mu)/\sigma \qquad (1.)$$

where Z is the Z-score, x is the data point, μ is the overall mean and σ is the standard deviation (Geher & Hall, 2014). When the Z-score is zero, the data point's score is equal to the mean.

In Paper IV, the nine management practices monitored were analysed using a linear mixed effect model (lme function in the nlme package) with maize yield as response variable, the nine practices as fixed effects together with area, year and season, and farm and pair of project and control farms as random factors. Stepwise Akaike information criterion (AIC) was then used to identify practices contributing to explaining the correlations with maize yield. The effects of number of trees and types of trees on maize yield were also tested in Paper IV, using the same functions. For trees, the fixed factors included study area, season and total number of trees, and type of trees divided into fodder trees, timber trees and fruit trees. Farm was a random factor. When comparing mean seasonal maize yield per farm for two seasons and four years, a linear mixed effect model (lmer function in the lme4 package) was used with four fixed factors (treatment, area, year, season), which were tested as direct effects and with all two-way interactions included in the model. In this analysis, only paired project and control farms were included. Both individual farms and pairs of farms were set as random factors in the model. A Chi-square test was used to identify dependencies between food self-sufficiency and KACP participation.

In order to synthesise data from the four papers, some additional analyses were carried out. These included tests from the individual interviews (Paper II) and from KACP (Paper IV) of the single measures that were similar for both studies, as well as the learning sources divided into groups of internal, external, horizontal and Vi Agroforestry. These were analysed using the lm function, with gender, site and access to advisory services or not as the three fixed factors for Paper II data, and region and treatment as fixed factors for Paper IV data. Significance level for all analyses was set to $P<0.05$.

Table 1. *Statistical analyses carried out in R for the thesis (Papers I-IV). (+) separates between main effects of different factors, (:) indicates a single interaction and (*) implies that all possible interactions were considered between the respective factors. All factors within brackets have interactions with the factor outside the bracket.*

Paper	Statistical method	Factors	Response variables	Distribution
I	glmer function in lme4 package AIC, modavg	Fixed: (gender + site + training) * type of measure Random: farmer group	No of measures identified Scale of measure	Poisson, and observation level vector
I	lme function in nlme package AIC, modavg	Fixed: (gender + site + training) * type of measure Random: farmer group	Mean score of measures	Gaussian
I	glmer function in lme4 package AIC, modavg	Gender + site + training + gender:site + gender:training + site:training Random: farmer group	Number of times mention learning source, Elders, MoA, neighbours, Vi Agroforestry, other sources, common sense	Gaussian
II	lm function cld function in multcompview package	Gender * site * training	Use of measures Mean score of measures Vulnerability	Gaussian
II	Logistic regression, glm function Chi-2 test cld function in multcompview package	Gender * site * training	Learning sources Limitations	Binomial
III	lm function cld function in multcompview package Tukey's test	Settlement + (high tree density * low tree density * high livestock density * low livestock density) Co-variates: farm size and family labour	All ecosystem service indicators All farm priority key variables	Gaussian

Paper	Statistical method	Factors	Response variables	Distribution
III	lm function cld function in multcompview package Tukey's test	Settlement + (high tree density * low tree density * high livestock density * low livestock density) Co-variates: farm size and family labour	Indicators and variables based on proportions	Logit
IV	lme function in nlme package Stepwise AIC and lmer function in lme4 package	Fixed: management practice [1] + site + year + season Random: farm and pair of project and control farms	Maize yield	Gaussian
IV	lme function in nlme package Stepwise AIC and lmer function in lme4 package	Fixed: number of total trees + fodder trees + timber trees + fruit trees + site + season Random: farm	Maize yield	Gaussian
IV	lmer function in lme4 package	Fixed: treatment + site + year + season + all two-way interactions Random: farm and pair of farms	Maize yield	Gaussian
IV	Chi-2 test	Treatment	Level of food self sufficiency	Gaussian
THESIS (II and IV)	lm function cld function in multcompview package	Gender + site + training (II) Region + treatment (IV)	Use of each of mulch, cover crops, compost, terraces, ditches/water harvesting structures, no tillage Mean score of each of the measures	Gaussian
THESIS (I and II)	glm function cld function in multcompview package	(site + training + gender) * learning source	No of replies for external, internal, horizontal and Vi Agroforestry sources	Poisson

[1]No-tillage, crop residues for mulching, raw manure composting, cover crops, terracing field, water harvesting structures, removal of residues, raw manure to field, burning of residues.

4 Results

4.1 Rainfall variability challenges (Papers I and II)

Group interviews (paper I) and individual interviews (Paper II) both included a question on perceived challenges related to rainfall variability and the responses were similar in the two studies. Kisumu farmers mentioned both a larger number (on average) and more severe rainfall variability challenges than Trans Nzoia farmers. Both too little and too much rain, with droughts as well as floods, were common in Kisumu, while Trans Nzoia farmers were mainly concerned about too much rain accompanied by strong winds and hailstones that could destroy crops instantly. Too little rain, and on some occasions floods, can also occur in Trans Nzoia. These challenges were not new to the farmers, but they perceived that their frequency and magnitude had increased since the 1980s. In both areas, rainfall was also perceived to be increasingly unpredictable in recent years.

4.2 Awareness of measures to deal with rainfall variability (Papers I and II)

During the 16 farmer group interviews in Paper I, a list of adaptation and coping measures was identified. After complementing the list through the 10 advisor interviews, a total of 81 adaptation and 13 coping measures, divided into 12 categories, were included (Table 2 in Paper II). The five categories with most measures comprised practices related to erosion control, crop production, tree production, livestock production and irrigation. Both in group interviews (Paper I) and among individual farmers (Paper II), adaptation measures were scored higher than coping measures. Farmers explained that coping measures often lead to decreases in on-farm labour, which could undermine farm development since adaptation measures were often labour-intensive.

The number of measures mentioned varied between 12 and 40 for the different farmer groups (Paper I). Groups of men mentioned more measures than groups of women, and Kisumu farmers mentioned more measures than Trans Nzoia farmers (Figure 7a).

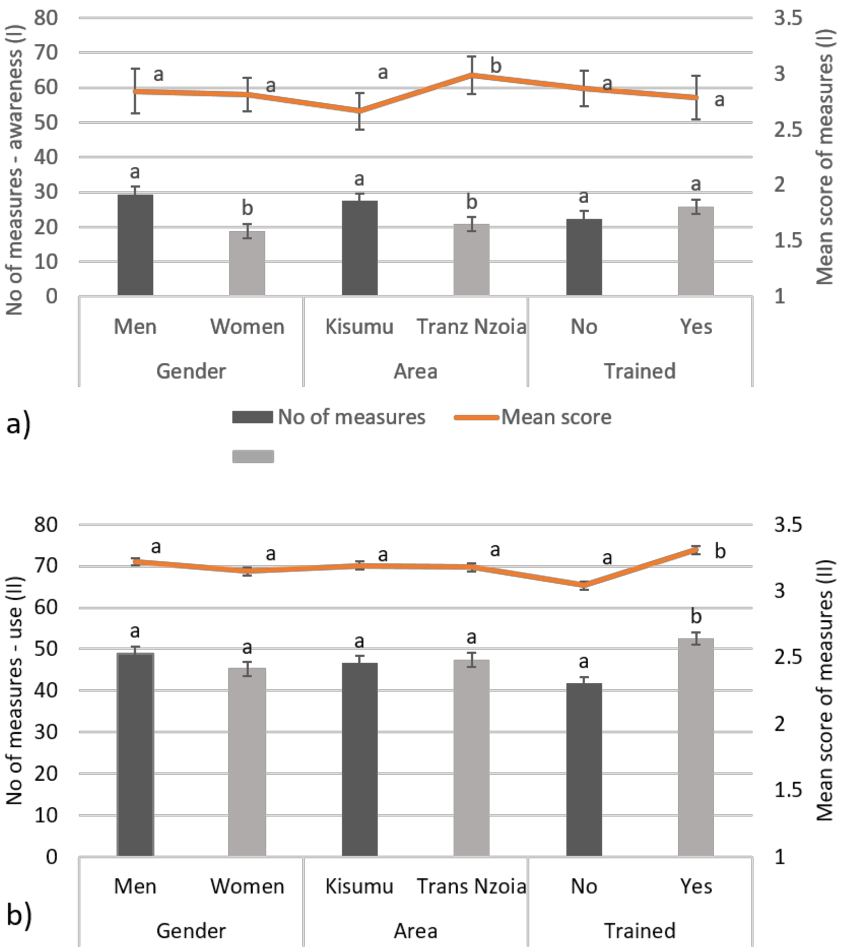

Figure 7. a) Number of measures that farmer groups were aware of and the perceived effectiveness scored between 0 and 5, where 0 means "no positive effect to adapt to or cope with rainfall variability" and 5 means that the "measure is enough alone to adapt to or cope with rainfall variability" (Paper I). b) Number of measures that individual farmers used and the perceived effectiveness scored between 0 and 5 (Paper II).

4.3 Use of more sustainable management measures for improved farm performance (Papers II and IV)

4.3.1 Effects of advisory services on the use of adaptation measures (Paper II)

Farmers with regular access to advisory services (hereafter referred to as 'trained farmers') used significantly (P<0.0001) more adaptation measures than farmers without regular advisory services (hereafter referred to as 'non-trained farmers'). An average of 48 of the 81 adaptation measures were used by trained farmers, compared with 36 measures by non-trained farmers (Figure 8a).

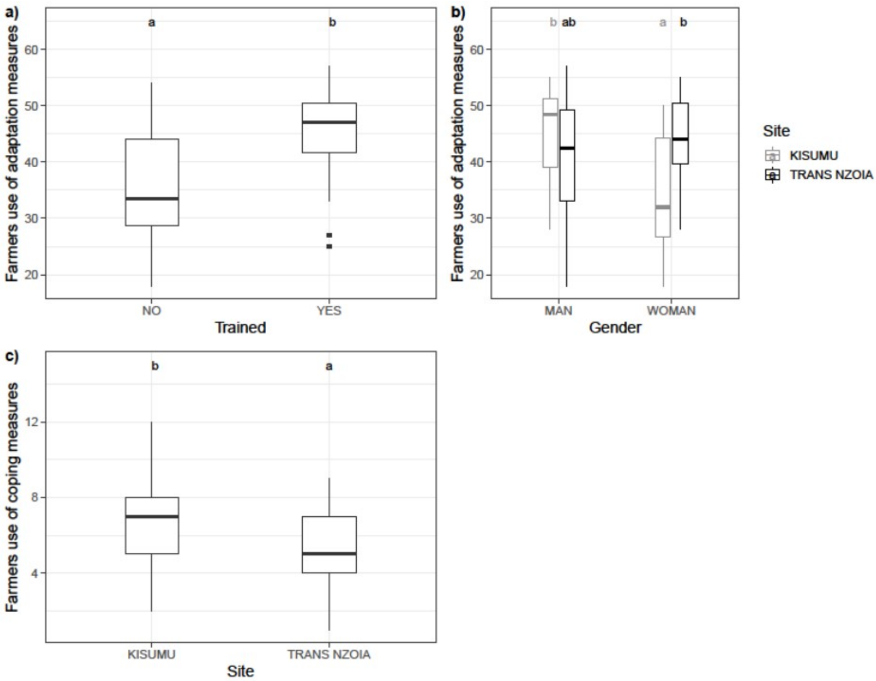

Figure 8. Number of adaptation and coping measures self-reported to be used by individual farmers (Paper II). a) adaptation measures used by trained (YES) and non-trained (NO) farmers, b) adaptation measures used by men and women in Kisumu and Trans Nzoia and c) coping measures used in Kisumu and Trans Nzoia. Boxplots indicate the number of measures used by 25, 50 and 75% of respondents (the interquartile range) and whiskers show the largest and smallest values within 1.5 times the interquartile range above 75% and below 25%. Trained farmers used more adaptation measures (P<0.0001) than non-trained and women used less measures than men in Kisumu, but not in Trans Nzoia (P=0.0007). More coping measures were used in Kisumu than in Trans Nzoia (P=0.0007).

Among all 94 adaptation and coping measures, the most (score >3.4) and least (score <3.0) effective measures were identified (Table 2). Trained farmers used a larger proportion of the most effective measures and a smaller proportion of the least effective measures than non-trained farmers. The following measures were particularly used more by the trained farmers: (1) Visit an agricultural training centre; (2) have trees to improve soil fertility; (3) have trees to improve the micro-climate and get more rain; (4) get knowledge through the group; and (5) sell firewood/charcoal. All except selling firewood/charcoal were scored >3.4. Erosion control measures were the most popular category of measures to use. Trained farmers used more erosion control measures (P=0.001), crop measures (P=0.0001) and tree measures (P<0.0001) than non-trained farmers.

Table 2. *Adaptation (A) and coping measures (C) used in the individual farmer questionnaire, organised into 12 categories depending on the nature and aim of the measure. The table includes mean percentage of farmers (n=80) using a measure from that category and, in brackets, the range of percentage of farmers using single measures within the category (Use), mean score and standard deviation (±SD) of score. Farmers only scored measures that they had used during the previous three years. Data modified from Papers I and II*

Type of measure	Name of measure	A/C	Use %	Mean score	±SD
Erosion control	Early ploughing, Early planting, Raised beds, Soil ridges[1], Add manure, Dig cut-off drain, Dig ditches, Plough/plant along contours, Double digging (incorporating manure by digging deep and cover with soil), Add mulch, Dig terraces, Grass strips, Add compost, Dry planting (planting before rain), Soil in sacks, Stone lines, Plant without ploughing, Use greenhouse	A	61 (8-95)	3.3	1.3
Crop production	New/short-term crop varieties, Plant traditional crops, Drought-resistant crops, Plant perennial crops, Water-tolerant crops, Plant cover crops, Plant 'under-ground' crops (root and tuber crops, groundnuts), Bananas in ditches, Relay cropping[1], Crops in nursery, Mushroom production[1]	A	62 (3-80)	3.3	1.3
	Early harvesting, Sell harvest at 'throw-away' price[1], Chemical on leaves to reduce moisture	C	53 (13-81)	2.5	1.5
Tree production	Have tree nursery instead of direct sowing[1], Plant trees for micro-climate/more rain[1], Plant trees as windbreak, Plant trees for soil fertility, Sell fruit from trees, Plant trees for erosion control, Sell timber, Plant trees to absorb water, Sell firewood or charcoal, Sell tree seedlings[1], Sell fodder from trees, Sell medicine from trees[1]	A	51 (1-95)	3.4	1.2

Type of measure	Name of measure	A/C	Use %	Mean score	±SD
Livestock production	Focus on livestock, Fence the farm[1], Take livestock to greener pasture, Rotational grazing, Plant fodder, Build raised cattle shed, Dry/store fodder, Reduce number of livestock and upgrade[1], Zero grazing system, Beekeeping, Establish fish pond	A	43 (6-76)	3.2	1.4
	Sell livestock	C	76	2.9	1.4
Irrigation	Timely watering, Roof catchment, Hand irrigation, Reuse of water[1], Micro-catchments on farm, Dig a water pan, Dig a well, Pump irrigation, Gravity irrigation, Drip irrigation	A	43 (0-96)	3.1	1.3
Off-farm	Keep a shop, Make and sell baskets, ropes, pots, Make and sell bricks, Go fishing in lake/river	A	27 (11-50)	3.2	1.2
	Trading, Sell labour, Sell land[1], Mine and sell stones	C	37 (9-65)	2.4	1.3
Food and cooking	Preserve food, Use raised energy-saving stoves	A	47 (28-66)	3.8	1.1
	Change eating habits, Less meals per day	C	75 (71-79)	2.2	1.4
External	Government build dikes	A	15	3.0	1.4
	Help from relatives, Relief food, Migration	C	30 (13-49)	2.3	1.4
Group related	Knowledge, exposure through group[1], Saving/loaning/marketing through group, Labour, encouragement from group[1]	A	79 (71-88)	3.5	1.1
Vegetable growing	Kitchen garden, Grow tomatoes off-season, Grow vegetables in a sack	A	49 (21-73)	3.1	1.3
Opportuni stic	Sell river water, Sell fish from flooded area, Harvest and sell sand	A	10 (5-13)	2.8	1.2
Other	Lease land, Visit agricultural training centre[1], Plant other area	A	60 (48-66)	3.2	1.2

[1]Measure only identified by advisors.

4.3.2 Effects of gender and biophysical setting on use of measures (Paper II)

A gender difference between the areas was found, with Kisumu women using less adaptation measures than men, while there was no difference between use of measures by women and men in Trans Nzoia (P=0.0007) (Figure 8b). Further, women in both counties used less irrigation (P=0.024) and off-farm measures

(P=0.018) than men. In general, Kisumu farmers used more coping measures than those in Trans Nzoia (P<0.0007) (Figure 8c). However, all interviewees had used between one and 12 of the 13 coping measures during the previous three years.

Despite higher awareness of measures in Kisumu, especially among men (Paper I), the general use of all measures was significantly higher only for farmers with regular access to advisory services (Figure 7b). The number of measures used by individual farmers (Paper II) was also higher than the number of measures raised in group discussions (Paper I) (Figures 7a, 7b).

4.3.3 Use of more sustainable agricultural land management practices on Kenya Agriculture Carbon Project farms (Paper IV)

The KACP methodology included promotion of a suite of sustainable agricultural land management practices, *e.g.* mulching, terracing and no tillage. After four years, 60% of project farmers implemented mulching and terracing, compared with 25% and 40%, respectively, at the start when advisory services started promoting these practices. Water harvesting practices (*e.g.* digging ditches) increased in frequency from around 10% at the start to 40% after four years, while composting of raw manure increased from 50% to 65%. The three most popular measures among project farmers were mulching, composting raw manure before application, and terracing fields. No-tillage was not popular and cover crop use initially increased from 10% to 55%, but decreased back to 10% in the fourth year of the project. On control farms, use of some measures was relatively high, with around 50% using mulch and around 40% composting their manure. However, use of terraces, cover crops and water harvesting structures was less common.

Tree planting, especially in terms of agroforestry, was another successfully promoted practice, as project farmers had on average 86 trees per farm compared with 48 for control farms, and the proportion of fodder trees was 19% on project farms compared with 4% on control farms. The most common species overall were *Grevillea robusta* (silky oak), *Markhamia* spp. (tulip tree) and *Albizia* spp. (pink silk tree).

4.3.4 Matching use and effectiveness of selected measures (Papers II and IV)

The adaptation measures studied in Papers I and II included, but were not restricted to, the sustainable agricultural land management practices that were promoted in KACP (Paper IV). The advisory services to which farmers had access in Paper II were similar to the services implemented as part of KACP and supported by the same NGO (Vi Agroforestry). When comparing the use of measures four years after the start of KACP with uptake of self-reported measures used during the previous three years among farmers interviewed in Paper II, it was found that the farmers interviewed generally reported greater use of measures (Figure 9). Further, several of the practices promoted in KACP were used to a larger extent by project farmers than by control farmers, including mulching (P=0.006), using cover crops (P=0.01), composting manure (P<0.0001), using terraces (P<0.0001) and using water harvesting technologies (P<0.0001). Similarly, trained farmers reported higher use of mulching (P=0.007), compost (P=0.006) and no tillage (P=0.02) than non-trained farmers (Paper II). Bungoma farmers in KACP more frequently composted their manure (P=0.0003), dug terraces (P=0.007) and used water harvesting structures (P=0.0001) than Kisumu farmers. On the other hand, Kisumu farmers more often used mulch (P<0.0001), cover crops (P<0.0001) and no tillage (P=0.015).

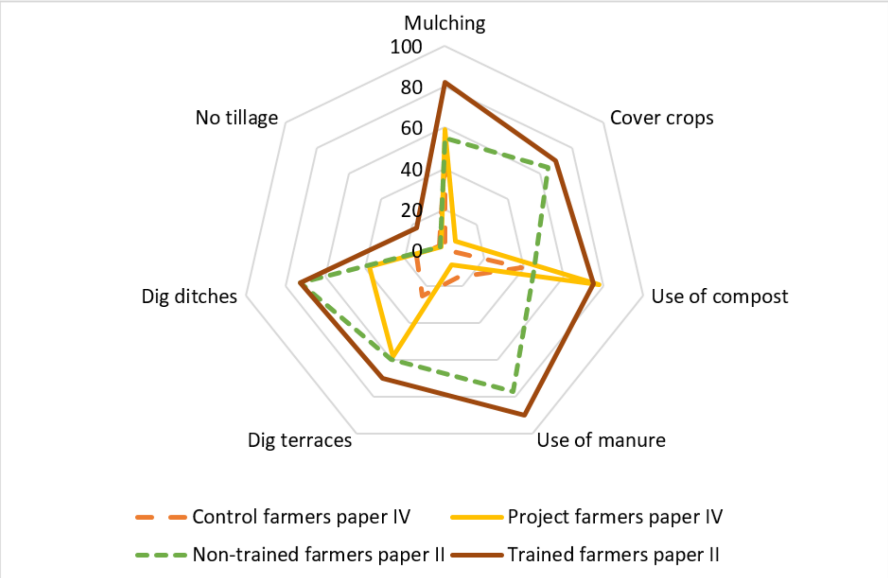

Figure 9. Use of selected measures (%) by control and project farmers in Paper IV (four years after the start of KACP) and by trained and non-trained farmers in Paper II (during the past three years, according to the farmer). The major difference in use of manure was likely due to farmers in Paper IV including composted manure as compost and farmers in Paper II double-counting the mixture of manure and compost they used as both manure and compost.

In KACP, only terraces and trees were positively related to maize yield. The average score given by farmers was 3.2 for terraces and a range of 3.4-3.9 for different tree planting measures (Paper II). However, mulch, manure and cover crops all scored higher than terraces (3.7, 3.5 and 3.3, respectively), but no significant relationship with maize yield was found in KACP. Planting without ploughing, *i.e.* no-tillage, only scored 2.3 and only 10% of farmers used it (Paper II).

4.4 Factors affecting adoption of measures (Papers I, II and IV)

Based on the results presented in section 4.3, access to advisory services generally appeared to increase the probability of using adaptation measures, especially effective measures like mulching, constructing terraces, cover crops and water harvesting structures. However, awareness and use of measures were not matched.

To better understand uptake of measures, learning sources for the measures and limitations to uptake were identified in the farmer group interviews (Paper I) and the individual interviews (Paper II) (Figure 10).

4.4.1 Learning sources for smallholders (Papers I and II)

Commonly mentioned learning sources (apart from the NGO, which was one of the selection criteria) were neighbours/friends, government and parents/elders. On dividing learning sources into internal (*e.g.* common sense or parents), external (*e.g.* government, NGOs, media) and horizontal (neighbours, group), in the group interviews external and internal sources of learning were mentioned more often (Paper I). Individual interviews instead reported a higher frequency of horizontal learning sources (Figure 10a). Groups of women (Paper I) reported fewer learning sources (especially government and parents) than men ($P=0.01$) and had to rely more on common sense, but the individual interviews showed no differences between women and men. Trained farmers learnt more from external than internal sources (especially international NGOs; $P=0.0008$), while there was no difference for non-trained farmers ($P<0.0001$) (Paper II). However, trained farmers learnt less from government and neighbours ($P<0.0001$ and $P=0.0007$, respectively) (Paper II). Trans Nzoia farmers also learnt more from external than internal sources ($P=0.04$) (Paper II). Respondents in Kisumu were particularly more likely to learn from parents (Paper I).

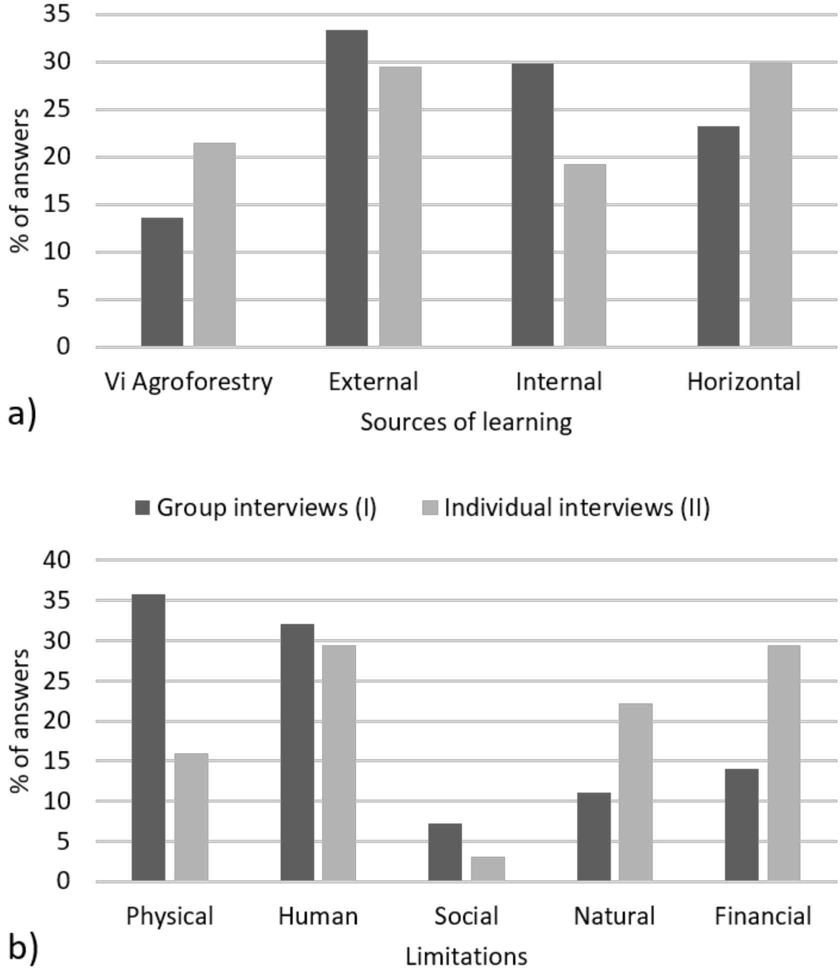

Figure 10. Responses in group interviews (Paper I) and individual interviews (Paper II) by smallholders when asked about: a) sources of learning about adaptation and coping measures, and b) limitations to use of these measures. The learning sources included the non-governmental organisation (NGO) Vi Agroforestry, which was part of the selection criteria in both studies, and therefore reported separately instead of being included in external sources. Other sources were divided between external (e.g. government, local and international NGOs, education, media, research organisations, companies), internal (e.g. parents, elders, common sense) and horizontal (e.g. neighbours, friends, groups). Limitations were divided between physical (e.g. material, tools, seed, fertiliser, animal, fodder, means of communication, electricity), human (e.g. knowledge, labour, time, laziness, attitude, interest, plan), social (e.g. agreements with others, security, a tradition of the work being done by men), natural (e.g. land, water, farm location, soil type, climate) and financial (e.g. money).

4.4.2 Limitations to uptake of measures (Papers I and II)

In both Paper I and II, the top two limitations were money and knowledge. Labour came third (Paper I), or fourth after land (Paper II). Kisumu farmers perceived land to be a more important limitation than Trans Nzoia farmers (P=0.02), which made it a more common limitation than labour (Paper II). Non-trained farmers were more limited by lack of knowledge in adoption of measures (P=0.009) compared with trained farmers. Trained farmers in Trans Nzoia were least limited by knowledge (P=0.02). Women were also more limited by knowledge than men (P=0.04).

In further analysis, the limitations were divided into the five types of capitals (physical, human, social, natural and financial) (Fang *et al.*, 2014; DFID, 1999) (Figure 10b). During group interviews (Paper I), physical limitations (*e.g.* tools, livestock, fertiliser or trees) were the most commonly mentioned, followed by human limitations (*e.g.* knowledge, labour, interest). The results from the individual interviews (Paper II) showed that human and financial limitations (money) were the most commonly mentioned. Mentions of natural limitations (*e.g.* water, farm location, soil type) were also more common in the individual interviews. Social limitations were the least commonly mentioned in both studies and were more often mentioned by women, who needed permission to perform certain measures from *e.g.* their husband, a neighbour, the village or the authorities.

In Paper II, farmers were also asked if they considered themselves less, more or equally vulnerable to the rainfall variability challenges identified, compared with their neighbours. A majority of farmers viewed themselves as equally vulnerable to their neighbours. However, the reasons for considering themselves more vulnerable were mostly lack of knowledge, money, land or livestock. Farmers considering themselves less vulnerable described themselves as being knowledgeable, having livestock (especially dairy cows), having a beneficial farm location and having trees on their farms. Women in Kisumu viewed themselves as significantly more vulnerable than other farmers.

4.5 Effectiveness of measures (Papers I, II and IV)

4.5.1 Perceived effectiveness of measures (Papers I and II)

No measure had an average score that was high enough to be considered sufficient to manage rainfall variability challenges alone. In the group interviews (Paper I), the clearest difference in perceived effectiveness was between adaptation and coping measures, where adaptation measures were rated more effective, which was also expected according to the definitions. Kisumu farmers rated the measures less effective than Trans Nzoia farmers (Figure 7a) and field measures were scored higher than landscape measures (Paper I). The same patterns for adaptation and field measures were also found in Paper II.

When looking in more detail at the scores given by individual farmers (Paper II), *e.g.* among the 12 categories (Table 2), food and cooking measures, group-related measures and tree production measures received the highest mean scores for adaptation. The most effective measure across all farmers was energy-saving stoves and the least effective was selling products at a 'throw-away price'. Trained farmers gave the most effective measures (score >3.4) higher scores (P=0.007) than non-trained farmers. The least effective measures (score <3.0) were scored higher in Kisumu.

Mulching was scored highest by trained farmers, trees to improve soil fertility was scored second highest and getting labour through a group was considered the third most effective measure. Non-trained farmers generally gave lower scores than trained famers (Figure 7b), and gave energy-saving stoves the highest average score, followed by preserving/storing food and ploughing and planting along contours.

4.5.2 Relationship between measures and maize yield (Paper IV)

The relationship between practising selected measures and maize yield was analysed. However, there was no information about the extent to which a measure was practised, *e.g.* the quantity of organic matter applied to a field when mulching. Terraces and trees showed positive relationships with maize yield (P=0.0004 and P=0.02) while no-tillage, crop residues used as mulch, raw manure composting, cover crops and water harvesting structures showed no significant relation with maize yield on the study farms. Overall, however, the management effects were small compared with differences between years or study areas.

4.6 Maize yield development in KACP (Papers III and IV)

The average maize yield on the 20 farms in Paper III, where one long-duration maize crop was harvested per year, ranged between 1687 and 2208 kg ha^{-1}. This is similar to the average maize yield in Paper IV, which ranged between 1008 and 1879 kg ha^{-1} for the first (long-rain) season and between 478 and 829 kg ha^{-1} in the second (short-rain season). This difference in yield between the rain seasons was strongly significant (P<0.001). Overall, farmers in Bungoma had higher yields than those in Kisumu (P<0.001) and KACP farms had higher yields

(P<0.001) than control farms (Figure 11). The yield increase was also different (P<0.001) between project and control farms, where project farms increased their yield mostly in the first two years of the project term and control farms had a one-year lag, with their main increases in the third and fourth years (Figure 11). Overall, however, the difference between KACP farms and control farms was similar at the start and after four years, and therefore the yield increases for KACP farms cannot be explained solely by participation in the project.

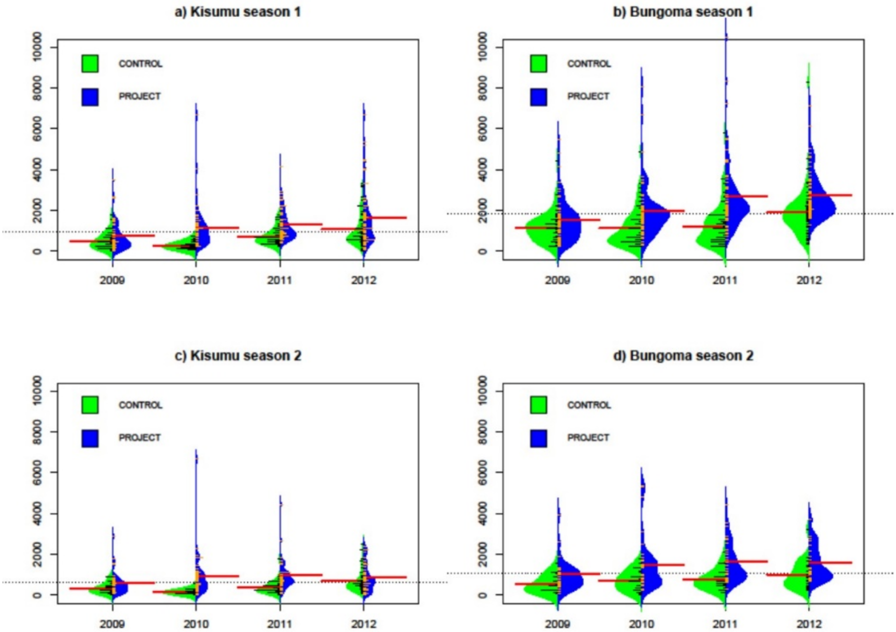

Figure 11. First and second-season maize yield (kg ha^{-1}) on project farms and control farms in Kisumu and Bungoma during the first four years of the Kenya Agricultural Carbon Project (2009-2012) (Paper IV). Maize yield in a) Kisumu during the long rains (season 1), b) Bungoma in season 1, c) Kisumu during the short-rains (season 2) and d) Bungoma in season 2. The lines indicate mean values for each distribution and the dotted line shows the mean for the whole plot.

4.7 Effects of tree and livestock density on ecosystem service indicators (Paper III)

4.7.1 Provisioning services

Among the provisioning services studied, *i.e.* maize and common bean yield, production of firewood, fruits, eggs and milk, and total value of farm production, none was significantly associated with tree or livestock density (Table 3). However, there was high variability between the farms included in Paper III. For instance, the total value of all crop, livestock and tree production had an average value of 268,000 Kenya Shillings (KES) for farms with high tree and high livestock density compared with 180,000 KES for farms with low tree or low livestock density. Instead, available family labour was found to have positive associations with fruit, milk and total farm production (Table 3, Figure 12a), whereas farm size was not related to crop, tree or livestock provisioning services.

The annual return on investment (ROI) was calculated for the three components (crops, livestock and trees) and for the four farm types (Figure 12b). The variation in ROI between farm types was largest for trees (range 1.3-48) and smallest for crops (range 3.4-8.3), while livestock had the lowest ROI (range 0.6- 6). The variation in ROI can be expected to be larger for *e.g.* perennial crops and trees with longer rotation times compared with annual crops. This is because annual ROI can vary considerably between years depending on the stage of production within the rotation or investment cycle. In the year of planting, trees will mainly involve expenditures, while the year of cutting trees will mainly involve revenues. Livestock can also show large variations in ROI between years.

On looking more closely at the incomes for the different farm types (Figure 13), it can be seen that farms with low tree and livestock density earned the majority of their income from off-farm jobs, while *e.g.* farms with high tree density and low livestock density had more than double the revenues from crop products than all other farm types. Farms with low tree density and high livestock density relied heavily on income from selling land and bricks, while farms with high tree and livestock density had the highest income from casual jobs, livestock and tree products.

4.7.2 Supporting and regulating services

Livestock and tree density showed no significant associations with the selected soil parameters used as indicators for supporting and regulating ecosystem services. However, higher concentrations of plant-available soil phosphorus and calcium and higher soil pH were found on smaller farms, following a negative relationship with farm size (Table 3). Labour was not associated with any of the supporting and regulating ecosystem services indicators.

Table 3. *Selected ecosystem service indicators for the study farms with high or low tree and livestock density (mean and 95% confidence interval (CI); n=20). Indicators measured in percentages were logit transformed. Significant results (P) in the last column are based on associations with the factors settlement (S), tree density (T) and livestock density (L), and with the co-variates farm size (F) and family labour (B), in a linear model. (+) = positive association, (-) = negative association. (Paper III)*

Indicators and units (farm average unless stated)	Low tree density mean (CI)[1]	High tree density mean (CI)	Low livestock density mean (CI)	High livestock density mean (CI)	Significant results
Provisioning ecosystem services					
Maize yield (kg ha^{-1})	2013 (1386-2640)	1882 (1255-2509)	2208 (1570-2845)	1687 (1050-2324)	
Firewood produced (1000 KES yr^{-1})	0.7 (0-11)	14 (3-24)	6 (0-16)	9 (0-19)	
Fruits produced (1000 KES yr^{-1})	3 (0-8)	7 (2-12)	4 (0-9)	6 (1-11)	B P=0.01 +
Eggs produced (no yr^{-1})	289 (0-619)	187 (0-518)	315 (0-652)	160 (0-496)	
Milk produced (1000 KES yr^{-1})	9 (0-22)	16 (2-29)	3 (0-17)	21 (8-34)	B P=0.04 +
Total value of produce (crop, livestock, tree) (1000 KES ha^{-1} yr^{-1})	180 (121-268)	268 (180-400)	180 (121-268)	268 (180-400)	B P=0.04 +
Supporting/Regulating ecosystem services					
Total soil organic carbon (SOC) (%)	1.78 (1.64-1.95)	1.83 (1.70-1.98)	1.76 (1.61-1.91)	1.87 (1.71-2.02)	S P=0.02
C/N ratio (soil carbon:nitrogen ratio)	13.9 (13.6-14.3)	14.0 (13.6-14.3)	14.2 (13.8-14.6)	13.7 (13.3-14.0)	
Available P (mg kg^{-1})	32 (22-43)	20 (10-31)	20 (9-31)	33 (22-44)	F P=0.008 -
Available K (mg kg^{-1})	405 (296-513)	365 (257-473)	313 (203-423)	457 (347-567)	
Available Mg (mg kg^{-1})	183 (146-220)	182 (145-219)	159 (122-197)	206 (168-244)	
Available Ca (mg kg^{-1})	853 (715-990)	921 (783-1058)	822 (682-961)	952 (812-1092)	F P=0.04 -
pH ($CaCl_2$)	5.14 (4.95-5.33)	5.17 (4.98-5.37)	5.06 (4.87-5.26)	5.25 (5.05-5.45)	F P=0.02 -
Bulk density in maize/bean field (g cm^{-3})	1.16 (1.08-1.25)	1.19 (1.11-1.28)	1.17 (1.09-1.26)	1.19 (1.10-1.27)	

Indicators and units (farm average unless stated)	Low tree density mean (CI)[1]	High tree density mean (CI)	Low livestock density mean (CI)	High livestock density mean (CI)	Significant results
Infiltration capacity in maize/bean field (mm $hour^{-1}$)	277 (248-306)	276 (247-305)	279 (250-308)	274 (245-304)	S P=0.002
Cultural ecosystem services					
Livestock species used for some cultural services (%)	2.2 (0.7-6.8)	1.8 (0.6-5.6)	3.9 (1.2-11.8)	1.0 (0.3-3.3)	
Tree species used for some cultural service (%)	54 (32-75)	7 (3-16)	28 (13-50)	19 (8-37)	T P=0.001 -
No of tree species used for some cultural service	3 (3-4)	6 (6-7)	5 (4-5)	5 (4-5)	
No of farms with ornamental plants	8	10	10	8	

[1]Where confidence intervals included negative values, they were adjusted to 0.

4.7.3 Cultural services

On average, three to six tree species contributed to beauty or recreation on farms with both low and high tree density. A larger proportion of tree species therefore provided cultural services on farms with low tree density (on average 54%) than on farms with high tree density (on average 7%) (Table 3, Figure 12c). The most common reasons for planting trees were to produce fruit, firewood, timber, shade and medicine. However, on farms with low tree density, cultural services (especially shade for recreation) had a high priority, since more than half of the trees were used for cultural services on these farms. No farmer planted crops for cultural services. However, 18 out of 20 farmers interviewed had plants for decoration purposes only.

There was no difference in the share of livestock species used for cultural services (*e.g.* as pets or for status) between farms with high or low tree and livestock density. Livestock were generally kept for productive reasons (to get milk, eggs, meat, manure or offspring) or in order to provide a certain service (help with ploughing, security, vermin control). Indirectly, both livestock and trees were also assets that could be sold if needed, and thereby acted as savings. Family labour and farm size had no associations with the cultural ecosystem services indicators.

4.8 Effects of tree and livestock density on farm priority variables (Paper III)

4.8.1 Nutrient management

Four indicators related to nutrient management were evaluated on the 20 farms in Paper III. The average amounts of amendments applied to crops ranged between 505 and 689 kg ha^{-1} for organic amendments (manure and compost) and between 91 and 147 kg ha^{-1} for inorganic fertilisers. No significant associations were found between nutrient management and either tree or livestock density, or family labour. However, a negative association was found between farm size and added organic amendments per hectare (Table 4). Regarding maize residues, livestock density had, as expected, a positive association with the proportion used for fodder. Farms with high livestock density used on average 38% of maize residues for fodder, compared with just 3% on farms with low livestock density. However, there was no significant relationship between tree or livestock density and the proportion of maize residues returned to fields, which was on average below 15% for all except crop farms (average 40%) (Table 4).

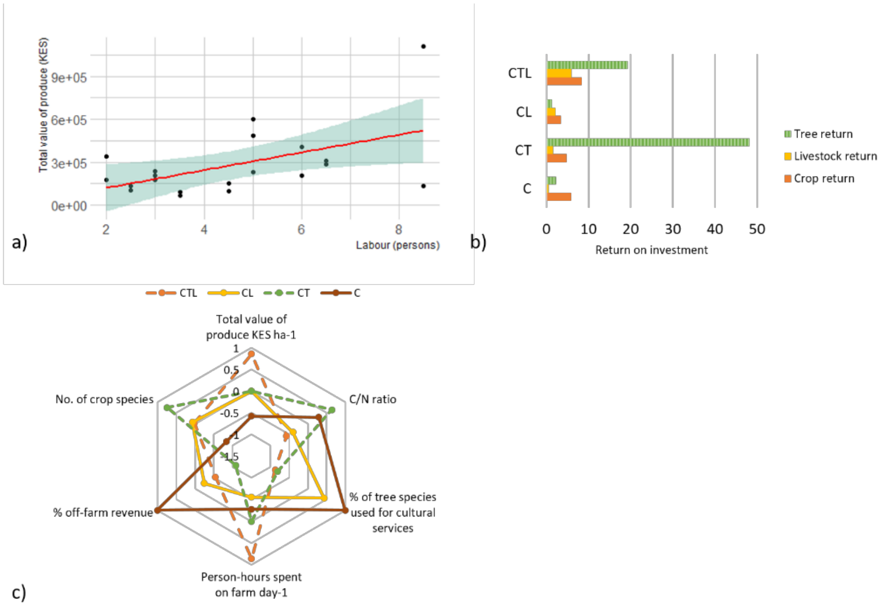

Figure 12. Selected results for the 20 farms (Paper III) displaying differences related to available family labour and high or low tree and livestock density. a) Significant positive relation between family labour and total annual value of produce (crop, animal, tree) expressed per farm area (ha) ($p=0.04$) (Kenya Shillings - KES). The line indicates the linear trend from the linear model and the shaded area shows the 95% confidence interval. b) Annual return on investment (ROI = (Revenue-Investments)/Investments) for the three farm components trees, livestock and crops in the high or low tree and livestock density farms (no statistical analyses done). c) Selected indicators of ecosystem services and key variables of farm priorities, represented as standardized Z-scores for the high or low tree and livestock density farms in a radar diagram including total value of produce (KES ha^{-1}), total carbon to nitrogen ratio in the soil, proportion of tree species used for cultural services, daily person-hours spent on farm-work, proportion of off-farm revenue of total revenue, and number of crop species. Crop-tree-livestock farms (CTL) were selected to have high tree and livestock density; crop-tree farms (CT) to have high tree and low livestock density; crop-livestock farms (CL) to have low tree and high livestock density; and crop farms (C) to have low tree and livestock density.

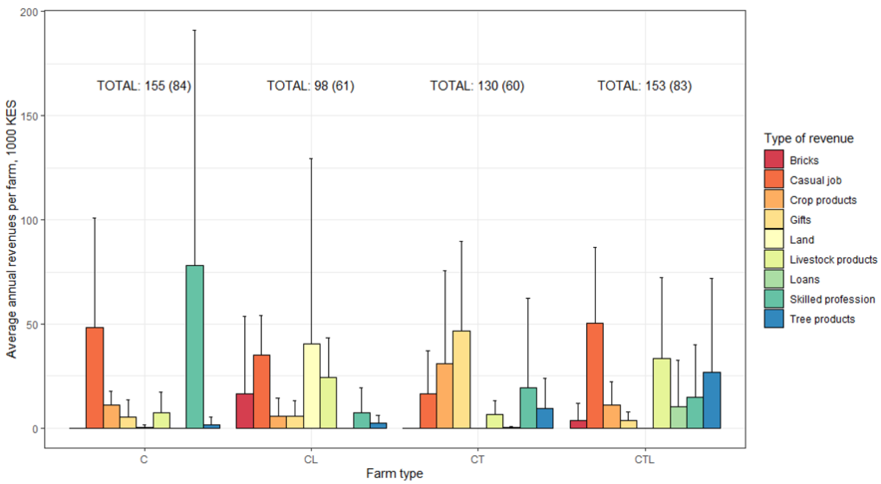

Figure 13. Average mean value and standard deviation of annual sources of revenues per farm, in thousand Kenya Shillings (KES). Total annual revenue per farm type are given in numbers above the histogram, with standard deviation in brackets. Crop-tree-livestock farms (CTL) were selected to have high tree and livestock density; crop-tree farms (CT) to have high tree and low livestock density; crop-livestock farms (CL) to have low tree and high livestock density; and crop farms (C) to have low tree and livestock density.

4.8.2 On-farm and off-farm resources

More man-hours of farm work per day were spent on farms with high tree density (6.2 hours) compared with farms with low tree density (4.0 hours) (Table 4). The highest workload was on farms with high tree and livestock density, 7.3 hours of work per day on average. Larger farm size also meant more time spent on farm work. However, available farm labour was not associated with the number of man-hours spent on farm work.

High tree density was also associated with a lower proportion of off-farm revenue in total revenues including value of produce. Proportion of off-farm revenue was on average 12% and 41% for farms with high and low tree density, respectively. Farms with low tree and livestock density had the highest proportion of off-farm income (on average 57%), but in real values no significant differences were found due to high variation in the data, *e.g.* the annual average off-farm income ranged between 49,000 and 86,000 KES.

4.8.3 Species diversity

The crop diversity was high, with on average nine to 12 crops per farm and year. Species diversity of crops, livestock and trees was positively related to available family labour in all cases (Table 4). The average diversity of trees ranged between nine species on farms with low tree density and 28 species on farms with high tree density. Crop, tree and fruit diversity values and Shannon's diversity index for trees were all positively related to tree density (Table 4). Livestock density was positively related to number of livestock species, but the average range was only 2-3 species.

4.9 Effects of trees, livestock and sustainable land management measures on livelihood (Papers III and IV)

4.9.1 Savings (Paper IV)

At the time of interview, farmers in the KACP were on average saving money to a larger extent than control farmers. More than 70% of project farmers reported saving money, whereas the figure for control farmers was around 50%. Project farmers saved more often than control farmers, and saved on average larger amounts per occasion. Among Bungoma farmers, 39% had farm inputs as their main expenditure, compared with just 14% in Kisumu, where instead 60% of farmers had food as their main cost. In Bungoma, there was a difference between project and control farmers, where 51% of project farmers spent most on education for their children, while 25% of control farmers still had to spend most on food and thereby only 27% had education as their main expenditure. The majority of farmers in both Kisumu and Bungoma had their main source of income from agricultural products.

4.9.2 Food self-sufficiency (Papers III and IV)

Purchased food as a proportion of total food consumed (in economic value) decreased both with larger farm size and higher livestock density (Table 4), but was not affected by tree density or family labour (Paper III). Almost half (45-48%) of all food was purchased on farms with low livestock density, while the proportion was 31% on farms with high livestock density. The proportion of revenues used to buy food ranged between 18 and 23% and was not affected by any of the factors analysed. Milk and fruit consumption had no significant associations with tree or livestock density. However, more available family labour, derived from the number of persons in the household, resulted in higher fruit consumption.

Table 4. *Results of selected farm priority variables for the study farms with high or low tree and livestock density (mean and 95% confidence interval (CI); n=20). Key variables measured in percentages were logit transformed. Significant results in the last column are based on associations with the factors of settlement (S), tree density (T), livestock density (L) and the interaction between tree and livestock density (T:L), and with the co-variates farm size (F) and family labour (B), in a linear model, (+) = positive association, (-) = negative association. (Paper III)*

Farm priority variables and units (farm average unless stated)	Low tree density mean (CI)[1]	High tree density mean (CI)	Low livestock density mean (CI)	High livestock density mean (CI)	Significant results
Nutrient management					
Annual organic amendments manure/compost (kg ha^{-1})	505 (180-829)	689 (365-1013)	547 (218-877)	646 (317-976)	F P=0.02 -
Annual inorganic amendments in maize/bean fields (kg ha^{-1})	101 (36-167)	136 (71-201)	147 (80-213)	91 (24-157)	
Maize residues returned to field (left or composted) (%)	21 (10-39)	12 (5-23)	23 (11-42)	10 (5-22)	
Maize residues used as fodder (%)	12 (4-30)	12 (4-28)	3 (1-9)	38 (16-65)	L P=0.001 +
On-farm and off-farm resources					
Land per capita (ha $person^{-1}$)	0.10 (0.06-0.13)	0.11 (0.07-0.15)	0.10 (0.06-0.14)	0.10 (0.07-0.14)	F P=0.0003 + B P=0.001 -
Average man-hours spent on farm work (man-hours day^{-1})	4.0 (2.7-5.4)	6.2 (4.8-7.5)	4.7 (3.3-6.1)	5.5 (4.1-6.9)	F P=0.04 + T P=0.05 +
Annual total off-farm revenue (1000 KES $farm^{-1}$)	86 (50-122)	49 (13-85)	85 (48-122)	50 (13-87)	
Off-farm revenues of all revenue and value of produce[2] (%)	41 (21-65)	12 (5-26)	24 (11-45)	23 (10-44)	T P=0.02 -

Farm priority variables and units (farm average unless stated)	Low tree density mean (CI)[1]	High tree density mean (CI)	Low livestock density mean (CI)	High livestock density mean (CI)	Significant results
Food and consumption					
Purchased food of total food consumed (%)	39 (30-47)	37 (29-46)	46 (37-55)	31 (23-39)	F P=0.04 - L P=0.02 -
Revenues used to buy food (%)	21 (15-29)	20 (14-27)	23 (17-31)	18 (13-25)	
Milk consumption (1000 KES $farm^{-1}$ $year^{-1}$)	6 (3-12)	10 (5-21)	7 (3-16)	8 (4-16)	
Fruit consumption (1000 KES $farm^{-1}$ $year^{-1}$)	4 (0-8)	6 (1-10)	4 (0-9)	6 (1-10)	B P=0.02 +
Species diversity					
No. of crop species $farm^{-1}$ $year^{-1}$	9.8 (8.8-10.9)	11.5 (10.4-12.5)	10.6 (9.5-11.6)	10.7 (9.7-11.8)	B P=0.02 + T P=0.03 + T:L P=0.03
No. of livestock species	3.1 (2.6-3.7)	2.7 (2.1-3.3)	2.4 (1.9-3.0)	3.4 (2.8-3.9)	B P=0.01 + L P=0.04 +
No. of tree species	9 (4-15)	28 (22-33)	17 (12-22)	20 (15-25)	B P=0.02 + T P=0.0004 +
No. of fruit species	1.1 (0-2.2)	2.6 (1.5-3.8)	2.1 (1.0-3.3)	1.6 (0.4-2.7)	T P=0.05 +
Tree diversity Shannon index	1.47 (1.17-1.76)	1.97 (1.67-2.27)	1.79 (1.49-2.10)	1.64 (1.34-1.95)	T P=0.02 +

[1]Where confidence intervals included negative values, they were adjusted to 0.

[2]Gifts to the household are not included in off-farm income or total income, but are shown in Figure 6 in Paper III

Perceived food self-sufficiency was higher on average for farms with low livestock density (Paper III), with 40% producing enough food for 10-12 months and 30% producing enough food for up to six months (Figure 14). Farms with high livestock density had the lowest average perceived food self-sufficiency, with 20% producing enough food for 10-12 months and 50% producing enough food for up to six months. The results for tree density showed the opposite pattern, with higher perceived food self-sufficiency on farms with high tree density (Figure 14).

KACP farms had significantly higher ($P<0.001$) perceived food self-sufficiency than control farms (Paper IV). There was also a tendency for higher self-sufficiency levels in Bungoma compared with Kisumu. Only 18% of control farmers considered that they had enough food for 10-12 months, compared with 32% of KACP farmers (Figure 14). Moreover, 36% of control farmers believed that they had enough food for up to six months, while the corresponding value for project farmers was 14%.

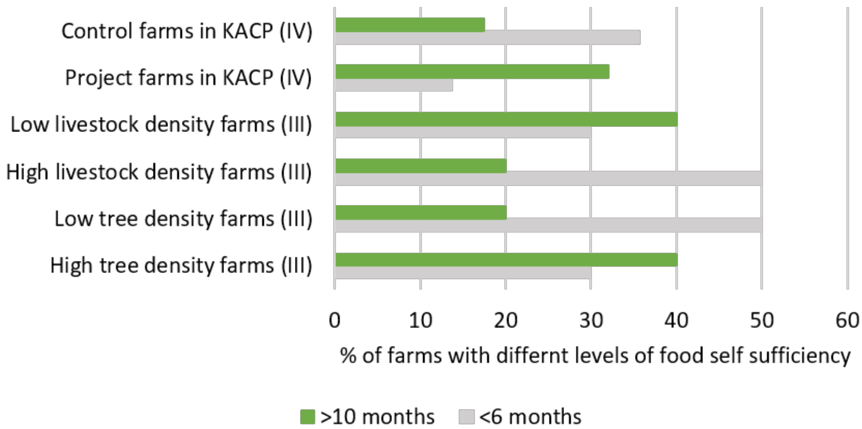

Figure 14. Levels of perceived food self-sufficiency on control and project farms in the Kenya Agricultural Carbon Project (KACP) (Paper IV) and on farms with high or low tree and livestock density (Paper III). The difference between control and KACP farms was significant.

5 Discussion

Whether discussing adaptation to climate change, sustainable farming practices or carbon emissions reductions, the same set of management measures are central to the solutions, including *e.g.* agroforestry, mulching, cover crops and efficient use of crop residues and manure. This thesis examined the question of what farmers do and why. Results obtained in the four field studies showed clear disparities between smallholders' awareness and adoption rates of farm management measures, and the perceived and actual effectiveness of some measures. Some indications of how and what smallholders prioritise and why were analysed. This information also shed some light on potential future research areas and policy implications.

5.1 Smallholders are aware of changes in rainfall

Both past numbers and future predictions of average rainfall and temperatures and their variability all show increasing trends in large parts of sub-Saharan Africa (Gebrechorkos *et al.*, 2019; Ayanlade *et al.*, 2018; Baede *et al.*, 2007). At the same time, droughts are becoming more frequent and more severe (Linke *et al.*, 2020). Local studies in Western Kenya confirm the perceptions of farmers and show that rainy seasons are getting more diffuse and unpredictable, while at the same time maximum and minimum temperatures are rising, all of which can affect water availability (Saalu Faith *et al.*, 2020; Gebrechorkos *et al.*, 2019; Sagero *et al.*, 2018; Wetende *et al.*, 2018). Realising that change is occurring is the first step for farmers in adapting to a changing situation (Deressa *et al.*, 2011; Maddison, 2007). Smallholders in the two regions of Kenya studied in this thesis reported increasing challenges related to rainfall variability, which was used as a proxy for climate change (Paper I). Farmers' perceptions confirmed their ability to detect climate patterns (Linke *et al.*, 2020; Ayanlade *et al.*, 2018). Differences in the magnitude of the challenges experienced by the two study areas were related to their topography, altitude and soil types. Since the rainfall amounts were similar in the two areas, lower rainfall variability or cooler temperatures in Trans Nzoia could have made droughts less common in that area. Trans Nzoia is located in the Kenyan Highlands, at around 2000 m asl, whereas Kisumu is located on the shores of Lake Victoria at 1100 m asl. Kisumu also has more challenges with floods, due to its flatter topography and less permeable soil types. While the biophysical setting and farm location play important roles in the severity of rainfall-related challenges experienced, and the coping measures farmers may be forced to undertake, other factors also play key roles in the preparedness or vulnerability experienced by farmers. Factors identified as contributing to vulnerability in the study areas included smaller farm size due to increased population density and the practice of growing maize, rather than more drought-tolerant traditional crops such as sorghum and cassava, which would be more suitable for the region (Kebede *et al.*, 2019; Deressa *et al.*, 2011).

5.2 Experience creates awareness of measures

The comprehensive list of measures for adapting to or coping with rainfall variability challenges mentioned by farmers during group interviews showed that these farmers had a high level of understanding of adaptation and coping mechanisms (Paper I). In some cases, farmers utilised the challenging situation in which they found themselves and found new ways to earn money. For example, during floods they were able to sell some fish and sand that came with the flood water. The type of measures employed were more or less similar between the regions and were also similar to earlier findings (Bedeke *et al.*, 2019; Kalungu & Leal Filho, 2018; Kamau *et al.*, 2014). The measures mentioned by the farmers included all the measures promoted in the KACP (Paper IV), where carbon credits are obtained for biomass (trees) and soil carbon sequestration, with payment upon delivery (Öborn *et al.*, 2017b). Basically these same measures (*e.g.* mulching, agroforestry and terraces) are beneficial for both more sustainable agricultural land management and more resilience to climate change, which is encouraging. The measures that farmers were aware of included mainly adaptation measures, which have more positive effects on farm production than coping measures. Therefore, the main focus of this discussion is on adaptation measures, unless otherwise specified.

There was no significant difference in awareness of adaptation measures between trained and non-trained farmers, but there was a difference in their pattern of use, with trained farmers using more adaptation practices (Paper II). This indicates that experience of a challenge, which results in awareness, is not enough to generate a response to the challenge. Instead, it appears as though knowledge and training increase the likelihood of uptake of measures, which is similar to previous findings (Maddison, 2007). The men surveyed in this thesis were aware of a larger number of measures than the women. This can probably be explained by the facts that the men were educated to a higher level than the women and had better access to learning sources. The higher awareness of measures mentioned in Kisumu was possibly a consequence of the more extreme rainfall-related challenges there, which had given farmers more experience of trying to manage the challenges. In particular, they had greater awareness of more opportunistic and off-farm adaptation measures.

5.3 Awareness is not enough to ensure uptake of measures

There is a major difference between farmers being aware of different management measures and using these measures. Relatively simple technologies such as terraces, reduced tillage, mulching, water harvesting and use of chemical fertiliser and organic manure can have comparatively low uptake rates, even though farmers are aware of them (Kalungu & Leal Filho, 2018). However, in this thesis the uptake was relatively high. Research has shown that when climate variability puts stress on households, it is rare for these households to focus on soil fertility management and thus they risk entering into a negative spiral of soil degradation (Valbuena *et al.*, 2015). Coping measures were used more or less by all farmers studied in this thesis, but to a larger extent in Kisumu where the rainfall variability was more extreme (Paper II). Use of coping measures caused a lack of labour and other physical resources such as livestock, trees or land (Paper II), confirming that smallholder farmers have restricted opportunities to implement adaptation measures (Bryan *et al.*, 2011). This can explain why the patterns of awareness and use of measures did not align. It appears as though awareness mainly reflected the need for measures, with Kisumu farmers needing more measures, but not having enough capacity to adopt them.

The fact that the number of measures used by an average farmer was larger than the number of measures known to a group also points towards the difference between having experience of a situation and having knowledge about it. Most farmers likely did not see the link between certain measures they use and the challenges they have experienced. Knowledge and understanding of *e.g.* why to plough and plant along contours is needed in order to link that measure to reduced erosion and increased water infiltration, which can make the difference between a crop surviving or not. When advisory field staff added measures to the list (Paper II), clear cause-effect thinking was apparent for several measures. Advisors added *e.g.* ‘visiting an agricultural training centre’ and ‘getting knowledge or labour through a farmers' group', which were aiming directly at acquiring knowledge or labour assistance, two of the most common limitations to use of adaptation measures. The same measures were also among those showing largest difference in use between trained and non-trained farmers, with trained farmers using them more. No group of farmers suggested any measure (Paper I) that directly led to a better position for managing the limitations to uptake.

5.3.1 Overall use of adaptation measures was high

The overall use of some measures was found to be higher in this thesis than reported in other studies (Kalungu & Leal Filho, 2018; Kamau *et al.*, 2014). This was probably related to the focus of the studied advisory services on overcoming some of the limitations farmers experienced, such as knowledge, credit, trees and labour assistance, which thereby enabled uptake of the measures (Figure 15). High use of adaptation measures can also be connected to the high dependence on farming in these areas of Kenya.

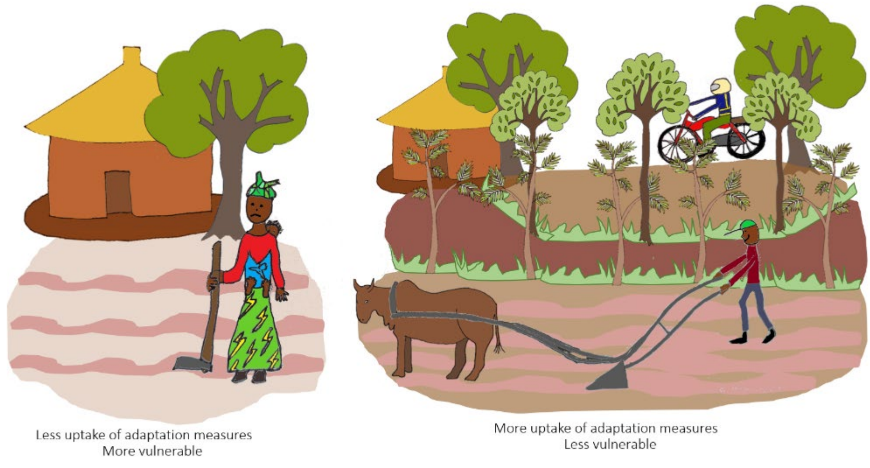

Figure 15. Two farmers representing two directions of vulnerability. Left) A low-educated woman with a flat small farm, no livestock and few trees, simple tools, and lack of labour and external sources of knowledge on farming. Right) An educated man with a larger, slightly undulating farm, with livestock and many trees, labour-saving tools and access to external sources of knowledge on farming.

The uptake of adaptation measures was high (Paper II), especially for measures perceived as effective, such as agroforestry, mulching, contour farming and cut-off drains (71, 69, 71 and 80%, respectively, compared with 6, 28, 35 and 33%, respectively, in Kamau *et al.* (2014)). On the other hand, the levels of no-tillage, terracing and use of manure (composted or raw) (10, 65 and 84%, respectively) showed similar (low and high) uptake as in Kamau *et al.* (2014) (7, 54 and 75%, respectively). While trained farmers used significantly more adaptation measures than non-trained farmers, non-trained farmers still reported relatively high use of some measures (Paper II). This could indicate a spill-over effect to non-trained farmers, which is common, through horizontal farmer-to-farmer learning (Krishnan & Patnam, 2014; Mercer, 2004). Farms in the study areas are small, with farmland adjacent to the homestead and located next to each other in the villages, which exposes farmers to what their neighbours are doing and how well it works.

Erosion control measures were most commonly used in relation to rainfall variability (Paper II). Those measures divert water to where it is needed. The most common measures used in Paper IV (mulch, terraces and composted manure) are all related to water infiltration and/or soil structure, which affects water flow and the water-holding capacity of the soil. Adoption of these measures increased for KACP farmers during the four years of the project studied in Paper IV, and was significantly higher for several practices than on control farms after four years. However, adoption among the neighbouring control farmers (whose farms were located only two farms away from the KACP farms) was also relatively high for some measures. An earlier study of the KACP areas found significant uptake of promoted practices among households targeted by Vi Agroforestry and also among farmers living in the same area, but not involved in the project (Hughes *et al.*, 2018), showing that ripple effects occur. Neighbours and friends were found to be the most common learning sources, especially among non-trained farmers (Papers I and II).

5.3.2 Trained farmers use more and better measures

Although non-trained farmers and trained farmers were aware of equal numbers of measures, trained farmers used the measures to a larger extent and had better ability to choose more effective measures. Knowledge has been identified previously as having a positive influence on adoption of more sustainable measures, as have *e.g.* plot size, market access and labour access (Phuong *et al.*, 2018; Kamau *et al.*, 2014). Knowledge provided through extension services reaches smallholder women to a smaller extent, due to cultural reasons and legal lack of rights, and women are therefore negatively affected by rainfall variability challenges to a larger extent (Gurung *et al.*, 2006; Doka & Monimart, 2004). Women also have problems finding time to attend training events, due to domestic responsibilities (Lee *et al.*, 2015). In this thesis, women knew of fewer measures than men (Paper I) and non-trained Kisumu women adopted the fewest measures (Paper II). Another study in Kenya found that gender did not influence awareness of measures, but that female-headed households implemented fewer measures (Kalungu & Leal Filho, 2018). A difference was found in this thesis between women in Trans Nzoia, who used as many adaptation measures as men, and women in Kisumu, who used fewer adaptation measures than all other farmers surveyed (Paper II). This difference could be due to the fewer external learning sources for women (Paper I) and for farmers in Kisumu (Paper II). It could also be due to the lower level of education among Kisumu women compared with women in Trans Nzoia (15 and 60% have secondary education, respectively). Education is important in empowering women (Sell & Minot, 2018) and also in making them less vulnerable to climate change (Mengistu, 2011; Mertz *et al.*, 2009). Empowering women, *e.g.* through education, has been found to have positive effects on farm productivity in another study in Western Kenya (Diiro *et al.*, 2018).

Trying new measures is risky for smallholders. Therefore it is important that research and development projects direct attention to the barriers to adoption, especially for the poorest smallholders. The choice of management practices in agriculture is important for productivity and sustainability. It can make the difference between the agricultural sector being one of the main sources of greenhouse gas emissions or acting as a net sink and enhancing ecosystem services (Potma Gonçalves *et al.*, 2018). Promoted measures need to have enough evidence of positive effects for smallholders (*e.g.* in terms of yield) to ensure that productivity and adaptation aims are prioritised. Only when the direct positive effects for smallholders are ensured should mitigation aims be considered (Cavanagh *et al.*, 2017; Mutoko *et al.*, 2014). In this thesis, no-tillage was *e.g.* rarely used by farmers (Papers II and IV), showed no tendency to have positive effects on maize yield and was scored lower than all other practice promoted by KACP (Paper IV), confirming results by Baudron *et al.* (2012). Such practices with questionable effects on yields should not be promoted to smallholders who cannot afford to risk losing production (Vanlauwe & Giller, 2006).

5.4 Reasons for adoption or lack of adoption

This thesis mainly studied the role of knowledge through advisory services, together with the role of gender and biophysical setting. The results confirmed the relationship between knowledge and gender, which seemed to be closely interlinked, since women had lower education and lower ability to attend training events or farm visits than men, as found in other studies (Felix *et al.*, 2010; Doss & Morris, 2000). Women and non-trained farmers also felt more limited by lack of knowledge compared with men or trained farmers. Gender should thus be considered when promoting and understanding technology adoption (Doss, 2001). Non-trained farmers had mainly neighbours or government advisors as learning sources for their measures and they had a smaller proportion of learning through external sources compared with trained farmers. A drawback with external sources of information is potential selection bias, as access to extension services has been found to be positively related to formal education, income and use of inputs in agriculture in some cases (George *et al.*, 2018). Higher education among trained farmers compared to non-trained farmers seemed to be the case in Paper I but no such tendencies were found in Paper II. This kind of bias can make farmers lose confidence in the advisor, which can impede adoption of new measures (Bedeke *et al.*, 2019; Lee, 2017). This bias will perhaps be reduced with new information communication technology, such as mobile phones to access farmers more easily, although that system also has weaknesses such as software malfunction and lack of personal contact (Tata & McNamara, 2018).

5.4.1 Smallholders are most limited by human and financial capital

Farmers themselves reported the main limiting factors for implementation of measures to be money, knowledge, labour and land (Paper II). This confirms that poverty can be one of the main reasons why *e.g.* agroforestry adoption among smallholders is low (Jerneck & Olsson, 2013), even if it can contribute in terms of food, income, carbon sequestration and reduced soil degradation (Henry *et al.*, 2009). However, in another study in the Trans Nzoia area, smallholders with the lowest resource endowment and mean farm size of about 0.5 ha were found to have the highest tree diversity (Nyaga *et al.*, 2015). Among group participants in this thesis (Paper I), 20% had farms smaller than 0.2 ha. Farms of this size limit the types of production possible and the time a farmer can afford to spend on the land. Ultimately, however, sub-division of land between inheritors into smaller farms cannot continue forever (Burke & Jayne, 2014) and will probably soon reach a point where farms start amalgamating and growing in size again (Jayne *et al.*, 2016).

Lee *et al.* (2015) found that labour to implement measures, knowledge on how to implement them and land availability were the main limiting factors for adoption of measures in KACP. Labour seems to be key to adoption of soil and water conservation measures particularly for smallholder farms that 'lose' labour due to coping measures. Agroforestry is also labour-intensive (Kebede *et al.*, 2018). Similar limitations have been reported elsewhere for adoption and spread of more sustainable measures, such as mulching, use of more manure on fields and intercropping (Karanja Ng'ang'a *et al.*, 2019; Phuong *et al.*, 2018; Bryan *et al.*, 2011). Moreover, credit schemes (*e.g.* VSLA in KACP) have been found to enable uptake of more sustainable measures (Bryan *et al.*, 2011).

All measures already being used by farmers are perceived, in one way or the other, to be profitable enough to use (Maddison, 2007). Sufficient knowledge is often what makes a measure profitable (Liu *et al.*, 2018). Horizontal learning about measures between farmers is common (Hughes *et al.*, 2018; Mercer, 2004) and could be one reason for the relatively high uptake of measures by the control farms in KACP (Paper IV), as also assumed in Paper II. However, without advisory services and sufficient knowledge, the measures may not be implemented in the most effective way (Paper II). There is then a potential risk of the measures never becoming profitable, due to lack of knowledge, and thereby gaining a poor reputation. Initial advice should therefore preferably be from external sources that could be complemented by employing farmer trainers that can disseminate and spread the measures effectively (Krishnan & Patnam, 2014).

5.4.2 Limitations and vulnerability are interrelated

Factors affecting the vulnerability of smallholder farmers were listed by the respondents in Paper II. Knowledge came first, both for those lacking it and being more vulnerable and for those having it and thereby being less vulnerable. Farmers feeling more vulnerable also reported lacking money, land and livestock, while those feeling less vulnerable said that, apart from having more knowledge they also had livestock, a favourable farm location and trees. Lack of these resources made farmers vulnerable, confirming that this is an important limitation to uptake of more sustainable land use management practices (Theriault *et al.*, 2017). Several of the resources concerned (*e.g.* livestock, trees, money) can act as insurance, which seems to be of high importance (Hänke & Barkmann, 2017; Lasco *et al.*, 2016). The reason why women in Kisumu felt most vulnerable compared with their neighbours may be that women have less control over several of the above mentioned resources such as livestock, trees, access to extension services, land, labour and money (Kiptot & Franzel, 2012). Females in Kisumu also had a lower level of education than females in Trans Nzoia.

Adoption of more sustainable measures is low in general among smallholders in Western Kenya (Kamau *et al.*, 2014), but the adoption rate has been found to increase with increased plot size, market and labour access, off-farm earnings and knowledge (Phuong *et al.*, 2018; Kamau *et al.*, 2014). This implies that the poorest farmers are likely to have the least possibilities to adopt measures, as found in this thesis. However, there are plenty of clear incentives that could improve that situation, and policies and interventions that could directly affect the use of more sustainable measures. In this thesis, adoption was primarily correlated with access to advisory services. Further, this thesis confirmed the important roles of labour and knowledge (Papers I, II and IV). However, the results also showed that farmers with a large proportion of off-farm earnings spent less time on farm work (Paper III), which contradicts earlier findings (Kamau *et al.*, 2014).

5.5 Inclusion of trees is one of the most effective measures

One reason why field measures (*e.g.* digging ditches or planting perennial crops) were considered more effective than landscape measures, that needed collaboration outside the farm (*e.g.* leasing land or selling labour), was that field measures were mainly adaptation measures, while several landscape measures were coping measures. The effects of the field measures are also more likely to be visible directly in the field (Papers I and II). The farmers surveyed were aware of many measures that could assist in adaptation to rainfall variability and that were also more sustainable. However, none of the identified measures had an average score that was high enough to be a solution to the challenge alone and therefore it is better to promote effective and synergistic measures in packages. (Paper II).

The rainfall variability challenge does not affect all farmers equally, since they have different levels of vulnerability. To find the best management practice for a certain farmer at a certain time, methods such as evidence-based decision analysis have been proposed (Shackelford *et al.*, 2019). However, it might be better in practice to look for a set of measures that can give synergistic effects, *e.g.* zero-grazing systems for livestock that make it easier to collect manure and planting fodder trees that can fix nitrogen. Synergies such as adding more manure to improve the water-holding capacity of soil and selling firewood when trees grow old enough can reduce the vulnerability of the farmer step-by-step and thereby enable increased adoption of more sustainable adaptation measures. When synergies have been identified, adoption of one measure can easily lead to increased adoption of other measures (Bedeke *et al.*, 2019).

Trained farmers were generally more likely to regard measures as effective, compared with non-trained farmers, which could perhaps be related to better knowledge on how to implement the measures. The measure considered most effective was having an energy-saving stove (Paper II). This is an indication of lack of trees and labour on farms, since the measure is not even connected to production. Energy-saving stoves, together with planting trees for soil fertility and preserving/storing food received the highest scores from farmers (Paper II) and are all known to be effective measures (Droppelmann *et al.*, 2017; Devereux, 2016; Dresen *et al.*, 2014; Sapkota *et al.*, 2014).

Maize yields (Paper IV) were positively related to terraces and total number of trees. The reason why only two measures showed significant positive relations could be that the measures were not quantified in terms of their level of implementation. The amount of dry organic material added or the area of a field covered by mulch, was *e.g.* not monitored when 'practising mulching' was noted in the KACP. In research projects, the focus is often on effects of certain technologies on yield, water run-off or soil erosion, based on field measurements following experimental designs (Kebede *et al.*, 2018). Under research conditions, most of the nutrient, soil or water conservation measures promoted by KACP showed positive effects on yield (Xiong *et al.*, 2018; Lal, 2015; Wu & Ma, 2015), although results for no-tillage systems on smallholder farms were inconclusive (Rosa-Schleich *et al.*, 2019; Ndoli *et al.*, 2018; Derpsch *et al.*, 2016). However, in a development project with thousands of participants, monitoring often requires compromises related to *e.g.* limited funding, allocation preferences (development or monitoring and evaluation) and excessive workload for project employees (Cole *et al.*, 2016). Farmers in Paper II perceived several of the measures promoted in KACP as being among the most effective measures (score >3.4), including tree planting and use of mulch, compost or manure. However, no-tillage got a lower score, of just 2.3.

5.6 Control farmers had a lag in increase in maize yield compared with project farmers in KACP

Maize yield data for smallholder farms were collected during the four initial years (eight seasons) of KACP. The continuous increase found among project farmers was not consistent with national yield patterns for Kenya during the same period (FAO, 2019; Mutsotso *et al.*, 2018). The results confirmed higher maize yields in the first (long-rain) season (Njoroge *et al.*, 2017), which was expected due to the longer rainy period and annual application of manure to fields in the beginning of the 'long rains'. The highland location Bungoma was expected and also confirmed to have higher yields due to cooler temperatures, and thereby less stress for the maize plants, as well as more responsive soils. Farmers in Bungoma also have a stronger focus on agriculture, while Kisumu farmers previously relied on fishing but are increasingly, although reluctantly, taking up farming (Ikiara & Odink, 1999).

The farmers participating in KACP had higher yields than control farmers already in the first year of the project, and this pattern remained consistent during all four years of the project. However, the yield increase during the four years showed no significant difference between project and control farms. There are several possible reasons for this, *e.g.* the measures promoted may have given an initial increase in yield on project farms, but yields then stabilised since KACP farmers were advised to use inorganic fertiliser carefully due to its negative effects on greenhouse gas emissions. Several studies describe inorganic fertilisers as necessary and important for boosting biomass (carbon) production and increasing yields in sub-Saharan Africa (Chen *et al.*, 2018; Vanlauwe *et al.*, 2017), if possible in combination with organic soil amendments (Vanlauwe *et al.*, 2001). Therefore the advice to use inorganic fertilisers carefully can be disputed and may have restricted the use of inorganic fertilisers among project farmers. However, since use of inorganic fertilisers was not included as a factor in Paper IV, this suggestion cannot be confirmed. Another reason for yields stagnating could be that project farmers simply put more effort into applying the sustainable agricultural land use management practices during the first years of engaging in the project.

Although farmers in general would like to have better access to advisory services (Stefanovic *et al.*, 2017), this thesis could not confirm any significant difference in maize yield increase from four years of participation in KACP, although use of more sustainable land management practices led to improved resilience. This was indicated by that the project farmers after four years in KACP had more trees, higher saving ability and food self-sufficiency than the control farmers. Hughes *et al.* (2018) also found that KACP had a greater positive impact on women than men. Women targeted by KACP advisors felt more empowered by the training, although more labour was required for implementing the recommended management practices (Lee *et al.*, 2015). These are important findings, especially since a focus on empowerment of women can reduce poverty and increase productivity (Diiro *et al.*, 2018). Further studies are needed to identify the key elements for increasing empowerment among women.

5.7 A diversified farming system including crops, trees and livestock helps to spread risks

In Papers I and II, all interviewees were asked which combination of crops, livestock and trees was best for managing rainfall variability. All groups except one in Paper I and 93% of farmers in Paper II believed that a combination of all three components was best. Trees and livestock were perceived to be superior to crops in relation to rainfall variability. Trees and livestock help to spread risk and are known to be more reliable and beneficial as insurances during unforeseen challenges (Hoang *et al.*, 2014; Tittonell, 2014; Baudron *et al.*, 2012). A woman in Trans Nzoia explained that it is important not to rely only on crops during periods of excess rain: "Maize cannot be dried during this time and therefore it is difficult with food even if you have maize. Dairy animals help a lot during this time, since we can sell the milk and thereby buy food". Another trained woman in Trans Nzoia said: "...fodder is sometimes waterlogged and cattle get diseases and can die. That is when fodder trees can really help, to give both poles for raised cattle sheds and fodder". A non-trained woman in Trans Nzoia commented on the food situation during the year: "Eating patterns change during May to July and instead of ugali from maize, people eat cassava, sweet potatoes or bananas. The number of meals is also reduced to one or two instead of three, since it is difficult to get food and dry firewood". These comments and other results clearly confirm the improved resilience a more diversified farming system can give (Quandt *et al.*, 2019). A comparison of the roles of livestock and trees in farming systems was made in Paper III.

5.8 Provisioning ecosystem services are not affected by tree or livestock density

The study of 20 smallholder farms (0.2-0.8 ha) did not show any significant effects of tree and livestock density on the selected indicators of provisioning, supporting or regulating services (Paper III). The results thereby confirmed previous claims that a wide range and density of trees or tropical livestock units (TLU) per hectare do not necessarily have a negative effect on maize or bean yield (Teillard *et al.*, 2017). One reason for this in the case of trees could be that the competition for light, water and nutrients between crops and trees can be compensated for by microclimate regulation by trees, which can improve or sustain crop yields through maintaining the optimal temperature longer during both day and night (avoiding extreme temperature stress) (Kuyah *et al.*, 2016; Lin, 2007). The reason why livestock did not affect crop yields negatively could be that the farmers with the smallest farms actually collected large parts of the fodder from outside their farms or chose to have smaller livestock such as chickens or goats. However, both trees and livestock need land resources that thereby cannot be used for crops.

Incorporation of trees on the farm (agroforestry) showed indications of an enhanced return on investment for livestock in this thesis, most likely due to the use of fodder trees assisting in providing nutritious fodder that can increase *e.g.* milk production (Makau *et al.*, 2020). Earlier studies have shown that ecosystem services are multi-faceted and thus difficult to assess, measure and compare

(Harrison *et al.*, 2018; Egoh *et al.*, 2012). To simplify the assessment, the focus in this thesis was on provisioning services in terms of products that were sold or used. An added number of or increased values of assets, livestock, trees or crops that were kept for future use were not considered, but could have affected the results. Moreover, indicators of ecosystem services are often insufficient to cover the multiple dimensions of the services and they are also difficult to weigh together (Harrison *et al.*, 2018; Layke, 2009). This could explain why significant effects on regulating and supporting services were not found. To better assess the effects on *e.g.* water regulation and nutrient cycling, these ecosystem services should preferably be studied not only at field scale but at farm and landscape level as well (Vialatte *et al.*, 2019; Kuyah *et al.*, 2017). Biological pest control is another regulating service which is often studied on landscape level (Rusch *et al.*, 2016). Another study carried out in the same settlements as used in Paper III showed that trees are important in decreasing pest abundances, not only due to creating habitats for natural enemies, but also in providing suitable microclimate conditions affecting the performance of both crops and pests (Guenat *et al.*, 2019). Microclimate could perhaps be a better indicator to study at farm level (Stigter, 2015).

5.9 Trees are important for cultural ecosystem services

Few earlier studies have included cultural services of farm components (Kuyah *et al.*, 2016). The results in this thesis showed that trees are highly important for cultural services (Paper III). Trees for recreation (*e.g.* shade, meeting place, beauty) were found in similar numbers on farms with low and high tree density, while trees for other purposes were lacking on farms with low tree density. These results contradict earlier findings that rural smallholders do not appreciate cultural services from trees (Mensah *et al.*, 2017). Trees also played a greater role for cultural ecosystem services than livestock in this study. Trees and livestock functioned as insurance or savings, according to the farmers surveyed (Papers I, II and III). However, young livestock can grow and be sold faster than trees, and therefore farmers often tend to prefer livestock over trees as their insurance (Jerneck & Olsson, 2013).

5.10 Soil nutrient concentrations are higher on smaller farms

In Paper III, manure and compost application rates showed a negative association with farm size, which gave higher concentrations of some soil nutrients (plant-available soil P and Ca) on smaller farms (although all farms were <1 ha). This was likely because the absolute amount of nutrients supplied with organic or inorganic amendments did not vary greatly between farms, resulting in higher soil nutrient concentrations on smaller farms. Sufficient inputs of organic amendments should benefit yields, resource conservation and finances (Adamtey *et al.*, 2016), but these resources are apparently not sufficient on these farms. Farmers rarely manage to add reasonable amounts of farmyard manure to their fields, as their animals often do not graze on the farm itself and as the relatively poor fodder returns manure with low nutrient concentrations. Storage of manure adds to the loss of nutrients (Tittonell *et al.*, 2010; Rufino *et al.*, 2007). Trade-offs for use of manure include using it as fuel or for maintaining mud houses (Berck & Teklewold, 2018; Kumar & Singh, 2016). Less than one-third of total nitrogen excreted by livestock actually reaches crop fields on the average farm in Western Kenya (Castellanos-Navarrete *et al.*, 2015). Large proportions of crop residues are used as fodder for livestock by Kenyan smallholders (Rodriguez *et al.*, 2017) or just burnt. While the use of crop residues for mulching was generally low, keeping livestock still seemed to increase the trade-offs for the resource. Since higher livestock density did not result in higher amounts of manure applied to the field, the nutrient balance will be more negative on those farms. However, if crop residues are fed to livestock and the manure is brought back to the fields, the process may not interfere significantly with carbon and nutrient cycling processes (Berazneva *et al.*, 2018). Crop residues should not be underestimated in terms of nutrient value. They are an easily available nutrient source for the next crop and, on the average farm in Western Kenya, where 38% of maize biomass consists stover and cobs, they have a total value of USD 0.07 per kilogram if recalculated as fertiliser (Berazneva *et al.*, 2018). If the value of this resource were clearly understood by smallholders, their decisions on if and how to use it might be easier.

5.11 Trees are labour-intensive, but can give multiple benefits

High tree density was positively related to both on-farm workload and on-farm proportion of income. There are two possible explanations for this; either the workload was high with many trees, and therefore the farmers had little time to look for off-farm income, or the farm produced more with more labour, so that was prioritised over off-farm work. The results also showed positive relations between available family labour and fruit, milk and total farm production, but it was not possible to see a link between available labour and estimated on-farm workload in that case. Available labour is perhaps a better measure of the amount of work carried out than estimated workload. It is difficult to know if more labour gives higher production, or if higher production sustains a larger family. However, the former seems more likely, since greater availability of family labour has been found to increase adoption of soil and water conservation (Bryan *et al.*, 2011) and on-farm workload has been found to be positively related to production (Kansiime *et al.*, 2018), even if it could not be confirmed in this study.

High tree density also showed a positive association with the diversity of trees and crops. This confirms that farming systems including perennials are being more diverse and also more labour-intensive than farms growing annual crops alone (Kotir *et al.*, 2020; Quandt *et al.*, 2019). However, diversity can give other benefits, in terms of *e.g.* greater biodiversity and more stable and improved ecosystem services, such as nutrient and water management, weed and pest control, soil health, and carbon sequestration (Rosa-Schleich *et al.*, 2019; Naeem & Li, 1997). The fact that project farmers in KACP had higher numbers of trees on their farms than control farms (Paper IV) partly confirms that higher farm diversity can be due to agricultural extension efforts (Mwololo *et al.*, 2019). It would be interesting to study this in more detail, since in Paper III access to advisory services was not considered. A connection between available labour and species diversity (for crops, livestock and trees) was confirmed in this thesis, and was probably also related to the higher workload (Kotir *et al.*, 2020; Garibaldi & Pérez-Méndez, 2019).

A challenge for farmers is that the ecological benefits of more diversified farming systems in terms of reduced risks and higher and more stable yields are long-term, and may therefore be insufficient to balance the short-term economic costs (Rosa-Schleich *et al.*, 2019). In some cases, high diversity on farms in combination with decreasing land holdings and increasing population can be a sign of desperation, rather than of adaptation, marking a household that is surviving, but not thriving (Conelly & Chaiken, 2000). Optimal levels of diversification of smallholder farms can improve food availability (Waha *et al.*, 2018). It is important for advisors to be aware of the optimal levels *e.g.* of tree and livestock density and diversity. Farms with little available labour likely simplify the work, so that they can manage within the labour available. Another aspect is that a decrease in crop diversity has been shown to directly reduce dietary diversity (Dillon *et al.*, 2015) although not seen for fruit and milk consumption in this study.

All farms in Paper III derived a considerable proportion of their revenue from off-farm income (skilled or casual labour), which is one way to reduce vulnerability (Bryan *et al.*, 2017). The proportion of off-farm income was higher for farms with low tree density, but the variation between farms was large and no significant differences in total off-farm income were found between the farm types. However, this thesis confirmed the relatively large proportion of off-farm income from formal employment among more off-farm specialised farms, in this case with low tree and livestock density (Kansiime *et al.*, 2018).

5.12 Project farmers in KACP had higher saving ability and food self-sufficiency

Smallholder farmers struggle to make ends meet and must minimise risks. They can reduce their vulnerability by acquiring knowledge, livestock and trees and by having a favourable farm location (Paper II). The majority of project farmers surveyed in Paper IV were initially unwilling to join the KACP, as they felt they needed more knowledge before they risked trying something new (Lee, 2017). Access to advisory services and VSLA schemes were built into the project design and offered to the participants as part of the project. According to the farmers, the carbon payment in itself did not incentivise participation, due to low carbon prices, as also found in other smallholder carbon projects (Hamrick & Goldstein, 2015; Swallow & Goddard, 2013; Stringer *et al.*, 2012; Henry *et al.*, 2009). However, yield increases were more attractive. Therefore, trust in the project developer (Vi Agroforestry) as the extension agency increased farmers' willingness to participate in KACP (Lee, 2017). The risk involved in joining could mean that better-off farmers are more likely to participate in such projects, which needs to be considered when evaluating the effects of the project (Lønborg & Rasmussen, 2014).

From Paper IV, it was clear that project farmers saved larger amounts and had a higher frequency of saving on average, most likely due to the VSLA concept initiated by the NGO (Mwansakilwa *et al.*, 2017; Ksoll *et al.*, 2016). Project farmers also showed a tendency to use their savings more for education than control farmers, which will maintain or even expand the gap in education, and thereby vulnerability, between farmers involved and not involved in the project.

Livelihood in terms of improved food self-sufficiency was monitored both in Papers III and IV. The higher food self-sufficiency perceived by KACP farmers, especially in Bungoma (Paper IV), can be attributed mainly to the higher yields, but also coincided with the higher tree density on project farms. Livestock farms in Paper III seemed to have a benefit in terms of milk, which lowered their expenditures for food items significantly, from about 40% to 30% purchased food in total food costs. The habit of drinking milk tea resulted in a high demand for milk. These results confirmed the positive effects on consumption of more diversified farms including livestock (Waha *et al.*, 2018). However, farmers with high livestock density perceived themselves as having less food self-sufficiency even though they apparently purchased a smaller share (by value) of the food they consumed compared with other farmers. Combining the results from Papers III and IV, it seems as though farms with higher livestock density actually do not purchase a smaller share of the food they eat because they are more self-sufficient, but rather because they cannot afford to purchase more food.

As highlighted earlier, there is a risk of livestock production actually reducing soil fertility (Duncan *et al.*, 2016). Thus the trade-offs with crop residues used as fodder and poor manure collection that seemed to 'dilute' nutrients on maize fields perhaps resulted in lower crop yields. Poor farmers also consume most of the food they produce, while it is more common for wealthier farmers to be able to sell products in order to buy food (Rufino *et al.*, 2009). Another factor to consider is that the price of milk is relatively high compared with the price of staple foods like maize, which means that those producing maize but buying milk may pay more than those producing milk but buying maize.

Another reason why trees tended to increase perceived food self-sufficiency, while livestock showed the opposite pattern (Paper III), may be due to the fact that growing fodder for livestock takes more land from crops than it yields in terms of other food products (Foley *et al.*, 2011). Lower competition between land for fodder and human food is necessary and urgent in the search for more sustainable diets (Röös *et al.*, 2016). In the study region, a way to increase resource use efficiency, reduce waste and minimise this competition for land could be to use more fodder trees (Balehegn, 2017) or to use smaller livestock that do not compete too much for land resources.

5.13 Limitations of the research

Papers I and II: The women interviewed were not always heads of households. If women who were household heads had been selected, the results might have been different. Questions about learning sources and limitations could have been asked for each measure in Paper II, as done in Paper I, in order to see if the sources of measures differed. The level of decision making/use of different measures (field, farm or landscape) should have been identified together with the targeted farmers, since this is an important aspect that is difficult to differentiate as a scientist.

Paper III: Larger farms could have been included, as well as farms with a larger range of livestock density and more farms in general. However, with larger ranges in farm size or number of livestock, larger differences between farms can be expected, so it would be more difficult to identify cause-effect flows. One option could have been to use tree density and livestock density as continuous variables with another selection of farms. This would have made it possible to assess associations between factors more clearly than with the present two-factorial design. The assessment of provisioning services would have benefited from inclusion of farm assets, apart from having flows to, from and within the farm. For regulating and supporting services, it would have been beneficial to include indicators for microclimate and biomass production on farm level. Increased understanding could have been achieved through collecting information on access to advisory services on the 20 farms.

Paper IV: This study was carried out within an ongoing development project. For research purposes, control farms should have been included from the beginning of the project and, perhaps even more importantly, located farther away from the project farms. Application of the different sustainable agricultural land management practices should have been more clearly defined and quantified, to enable more precise comparisons between farms.

6 Conclusions

Agriculture needs to undergo a transformation from being one of the causes of global environmental change to becoming part of the solution. Smallholders in sub-Saharan Africa cannot achieve this transformation alone, but with the right means they can perhaps play their part and act as good examples to large-scale farmers in the region and to farmers on other continents.

The overall conclusion from this thesis is that smallholders who manage to balance adaptation, productivity and other ecosystem services in a sustainable way have: access to credit and sufficient knowledge, land and labour. These resources are needed for implementation of synergistic farm management practices that create win-win relationships between farm components (*e.g.* crops, trees and livestock) in a diversified farming system, which also improves the resilience of the system. However, many smallholder farmers are not in this fortunate situation.

Smallholder farmers are well aware of local climate change and know about adaptation and coping measures to deal with climate variability. More experience of rainfall-related challenges increases awareness of adaptation measures and also use of coping measures. However, awareness alone does not enable smallholders to use adaptation measures, also knowledge is needed. The use of coping measures reduces the ability to practise adaptation measures and thereby makes farmers more vulnerable. Lack of money, knowledge, labour and other resources that can act as insurances, such as land, trees or livestock, also limit adoption of adaptation measures.

Although farmers with and without regular advisory services may be aware of similar numbers of measures, smallholder farmers with access to regular advisory services appear to use higher numbers of adaptation measures. They are also able to choose more effective measures and use these adaptation measures more effectively than smallholders lacking regular advisory services. No-tillage should not be promoted by advisors, as is perceived by farmers to have low effectiveness.

Through a higher level of education, better access to advisory services and more time for social networks, men are less vulnerable and use more adaptation measures than women, especially low-educated women.

Different practices for erosion control are the most commonly used type of adaptation measures. Regular access to advisory services leads to higher uptake of promoted sustainable land management practices, higher maize yields, better food self-sufficiency and more savings, as shown by the evaluation of the first four years of the Kenya Agricultural Carbon Project (KACP). In KACP, maize yield was positively related to agroforestry and terracing of fields, but the effects on maize yield could not be attributed solely to KACP.

More diversified farming systems, especially those including more trees, increase the proportion of on-farm revenues, recreation values and crop diversity, but may also increase farm workload. Trees can also have synergistic effects with *e.g.* livestock.

7 Implications and recommendations

In the current situation of smallholder agriculture in sub-Saharan Africa, there are many opportunities for positive transformation. A combination of formal advisory services, assisted by farmer trainers, for scaling up successful measures should be available to all smallholders. Women, especially those with little formal education, should be specifically targeted with advisory services on their terms. Gender aspects should be mainstreamed in all advisory services, in order for women to catch up in awareness, use and understanding of adaptation measures. A more holistic approach to advisory services should be applied, involving packages of synergistic measures and targeting the main limitations of farmers, *e.g.* by promoting village savings and loan associations and mainstreaming gender discussions. Credit opportunities are important, since savings seem to increase investment in education. Advice should cover risk spreading through more diverse farming systems (including crops, trees and livestock). It should not promote practices such as no-tillage or minimum tillage that prioritise mitigation aims, as they can pose risks to adaptation or production aims. Adaptation measures that do not need much capital, labour, land or special knowledge, but still give relatively short-term gains and long-term benefits, should be promoted in the early stages of advising farmers.

Knowledge was found to be key in this thesis, but there was clearly a need for other interventions in order to achieve high uptake of adaptation measures. Government schemes should provide farmers who want to develop their farms with easier access to *e.g.* credit to invest in more land or other short- or long-term investments. Providing opportunities for leasing simple machinery can be another option. Improved marketing facilities could also encourage farmers from a certain area to produce more of what is suitable to grow and sell, instead of what is preferred as household food. In order to better safeguard and value productive land, recommendations regarding the traditional agricultural land subdivision between descendants could be considered. In line with this, future research should focus on determining the minimum, optimal and maximum land holding sizes for diversified smallholder farming systems to provide food, income and other ecosystem services and resilience in a sustainable way.

Inclusion of trees on farms for cultural ecosystem services, such as recreation, was shown to be important in this thesis. Inclusion of trees on farms (agroforestry) was also found to be beneficial for the proportion of on-farm income and crop diversity, leading to improved resilience. A combination of fodder trees and livestock is an example of a synergistic relationship that could be promoted. The optimal tree and livestock density and diversity per unit area still needs to be defined for a specific region and should be studied, preferably with a larger number of farms and including a range of farm sizes even above 2.5 ha. Since inclusion of trees on the farm increases the workload, it is necessary to assess the available labour before suggesting a suitable tree density and diversity for a farm. When the farm is too small to sustain the family and members of the household prioritise off-farm income, this has to be considered in the agricultural advice and a simplified production system could be suggested.

There are plenty of opportunities, and smallholders in sub-Saharan Africa are both aware of, and willing to contribute to, more sustainable land management practices for their own and the common good. However, they need to balance short-term productivity with long-term resilience and different ecosystem services. The more vulnerable the smallholder, the higher the priority of short-term production aims. The challenge is to ensure that smallholders who want to remain in farming have the knowledge and means to start a transformation that is cost-effective, resilient and sustainable for them.

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Popular science summary

Small-scale farmers in sub-Saharan Africa are highly vulnerable to climate variability, but also have good potential to improve their sustainability and their production. These farmers struggle to make ends meet and in most cases live on less than one hectare of land. In this thesis, I looked at how Kenyan smallholders manage their farms in order to adapt to rainfall variability, improve productivity and maintain ecosystem services for a sustainable livelihood. I did this in field work carried out across a landscape gradient from Kisumu County by Lake Victoria to Trans Nzoia County in the highlands of western Kenya.

The first part of the work consisted of group interviews to assess whether the farmers had experienced rainfall-related challenges and the type of planned measures (adaptation measures) that could be used to be prepared for the challenges. I also asked about their use of coping measures in direct response to challenges and how that affected them. In individual interviews, I asked smallholder farmers about the measures they had chosen or been forced to use. The group and individual interviews were carried out in Kisumu and Trans Nzoia Counties, with differing conditions for agriculture. Women and men were interviewed separately, to find out if they had different experiences of the practices used to overcome current challenges. I interviewed farmers with access to regular agricultural advisory services and farmers with no such access. In another part of the study, I investigated the effects of high or low tree and livestock density on priorities, productivity and other ecosystem services. Finally, I compared farms that took part in a farm development project (Kenya Agricultural Carbon Project) with control farms, to examine differences in the use of sustainable land management practices, maize yield, food self-sufficiency or savings.

Smallholder farmers proved to be well aware of local climate changes. They were also aware of many different measures that can assist in adaptation and acute responses to rainfall variability. Awareness was not a guarantee for using adaptation measures, however, due to lack of money, knowledge and labour.

Through higher education, better access to agricultural advisory services and more time for social networks, men were able to use more planned measures than, especially, low-educated women. Farmers with access to regular agricultural advisory services used a higher number of planned measures and more effective measures. Maize yields were found to be positively related to terracing of fields and growing more trees on the farm, so-called agroforestry. Higher tree density increased the workload, but also the proportion of income that came from the farm. In addition, trees were important to farmers by providing shade for recreation.

As long as smallholders in sub-Saharan Africa do not have sufficient labour, land, money or knowledge, it will be difficult to convince them that more sustainable agricultural management practices will bring more benefits than costs. Based on the results in this thesis, I suggest that agricultural advisory approaches should better cover the whole farming system and be more inclusive, particularly as regards low-educated women. Agricultural advisors should promote packages of measures with positive interplays, encourage diversified farming systems to farms where this is feasible and focus on managing limiting factors such as access to credit, knowledge and labour, in order to increase the use of sustainable agricultural practices. This would help smallholders balance adaptation to rainfall variability and productivity with maintaining supply of ecosystem services for a sustainable livelihood.

Populärvetenskaplig sammanfattning

Småskaliga jordbrukare i Afrika, söder om Sahara, är bland de mest sårbara för klimatförändringar. Men de har samtidigt stora möjligheter att kunna förbättra sin produktion. Dessa bönder lever på gränsen till fattigdom och försöker försörja sig på en yta som ofta är mindre än ett hektar. Syftet med den här studien har varit att förstå hur dessa jordbrukare i Kenya bedriver sina jordbruk för att dels kunna öka sina skördar och dels anpassa jordbruket till varierande regnförhållanden. Detta samtidigt som de ska kunna använda sin mark på ett hållbart sätt som bibehåller viktiga ekosystemtjänster. Fältarbetet utfördes i västra Kenya i ett område som sträcker sig från Kisumu, vid Viktoriasjön, till Trans Nzoia på höglandet.

Den första delen av arbetet bestod av grupp-intervjuer för att ta reda på om bönderna upplevde förändringar i nederbörd och vilka metoder de använde för att anpassa sig till förändringarna. Sedan gjordes individuella intervjuer med bönder om vilka metoder de valt eller tvingats använda. Både intervjuerna i grupp och individuellt gjordes i Kisumu och Trans Nzioa som är två områden med olika förutsättningar för jordbruk. Grupperna som intervjuades var uppdelade mellan kvinnor och män och mellan bönder som hade eller inte hade tillgång till regelbunden jordbruksrådgivning. I en annan del av studien undersökte jag 20 gårdar i ett och samma område med hög eller låg träd- och djurtäthet för att förstå hur djur och träd påverkade prioriteringar, produktion och andra ekosystemtjänster. Slutligen jämfördes gårdar som deltog i ett kolinlagringsprojekt (Kenya Agricultural Carbon Project), med gårdar som inte ingått i projektet för att se eventuella skillnader i vilka jordbruksmetoder som används, storleken på majsskördar, självförsörjande-graden av mat och möjlighet till eget sparande.

Bönderna var väl medvetna om lokala klimatförändringar. De kände också till flera olika metoder för anpassning och hantering av variationer i nederbörd. Medvetenheten var dock ingen garanti för användning av metoderna. Det kunde bero på att de saknade pengar, kunskap och/eller arbetskraft. Män hade generellt sett högre utbildning, bättre tillgång till jordbruksrådgivning och mer tid för sociala nätverk. Män använde också fler anpassningsmetoder än kvinnor, särskilt jämfört med lågutbildade kvinnor. Regelbunden rådgivning ledde till en högre användning av anpassningsmetoder. Bönder med tillgång till rådgivning använde också fler av de metoder som bedömdes vara mer effektiva. Majsskördarna visade sig bli högre då bönderna gjorde terrasser på sina fält och då de samplanterade träd och grödor på gården, så kallad agroforestry. Fler träd ökade arbetsbelastningen för bönderna men träden ökade också andelen inkomster från gården. Dessutom var träd viktiga för alla bönderna i studien då de gav skugga, avkoppling och återhämtning.

Så länge småskaliga jordbrukare i Afrika, söder om Sahara, inte har tillräckligt med arbetskraft, mark, pengar och kunskap så kommer det vara svårt att övertyga dem om att mer hållbara jordbruksmetoder ger mer fördelar än nackdelar. Utifrån resultaten i denna studie föreslår jag ett rådgivningssystem som ser till helheten i jordbrukssystemet och är mer inkluderande, med fokus på lågutbildade kvinnor. Rådgivningen skall innehålla förslag på metoder som ger upphov till positiva samspel och förespråka varierade jordbrukssystem utifrån böndernas egna förutsättningar. Rådgivningen ska också fokusera på begränsande faktorer som tillgång till pengar, kunskap och arbetskraft och hur dessa kan avhjälpas för att öka användningen av hållbara metoder. Detta skulle kunna stärka bönderna så att de kan bedriva en gårdsproduktion som anpassas till klimatförändringar samtidigt som ekosystemtjänster bibehålls för en hållbar försörjning.

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I

AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS
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Smallholders' awareness of adaptation and coping measures to deal with rainfall variability in Western Kenya

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ABSTRACT

Farmers in Kisumu and Trans Nzoia counties, Kenya, were aware of more adaptation than coping measures for dealing with rainfall variability both on and off-farm. Interviews with female and male farmer groups revealed that they all experienced challenges related to increasing rainfall variability whether or not they had regular access to advisory services. Men identified more measures than women and had better access to learning sources. Farmers in Kisumu were aware of more measures than those in Trans Nzoia but thought them less effective. Money, knowledge and labor were the most limiting factors preventing the uptake of adaptation measures.

KEYWORDS

Advisory services; gender; land-use change; Vi Agroforestry

Introduction

For smallholder farmers, the distribution of rainfall is critical in rainfed agriculture, and seasonal rainfall variability can lead to crop failures (Ndehedehe, Agutu, and Okwuashi 2018; Rockström et al. 2010). Even if rainfall variability is often more challenging than changes in mean rain amounts for local communities, it is often neglected in research and advisory work (Thornton et al. 2014). For both researchers and local farmers, it can be difficult to determine whether local weather phenomena reflect normal variations or long-term climate change (Howe et al. 2013). However, adaptation measures are available (Ryan and Elsner 2016) and reported adaptation initiatives in Africa are increasing (Ford et al. 2015). There have been attempts to differentiate between adaptation and coping measures, with the main distinction being whether the measure is long term or short term, respectively (Mengistu 2011; Mertz et al. 2009; Rakshit, Padaria, and Bandyopadhyay 2016). The effects of adaptation and coping measures can differ widely, and it is therefore important to analyze them separately. Here, *adaptation* measures are defined as 'initiatives to reduce the vulnerability of natural and human systems against actual or expected climate change effects' (IPCC

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2007), and involve planning. *Coping* measures, on the other hand, are defined as survival-orientated, short-term solutions that are used because of lack of alternatives (Dazé, Ambrose, and Ehrhart 2009). Using adaptation measures can be the difference between being food secure or not among smallholders when rainfall variability is non-favorable (Kuhn et al. 2016). Building livelihood resilience, through the use of adaptation measures, is a way for smallholders to be better prepared for upcoming challenges in their production (Quandt, Neufeldt, and McCabe 2018). And to reach livelihood resilience, all five capitals (natural, social, produced, cultural and human) need to be considered (Bebbington 1999).

Long-term trends in East Africa show increasing temperatures and variations in rainfall where some areas showed decreasing trends. But Western Kenya showed a rainfall increase of on average 2.3 mm year^{-1} between 1962 and 2001, especially in the highlands (Gebrechorkos, Hülsmann, and Bernhofer 2019; Githui et al. 2009). East Africa is predicted to experience a temperature increase of 3.2°C (range 1.8–4.3°C) and a rainfall increase of 7% (range −3 to +25%) during the period 1980–2090 (IPCC 2007). However, the rainfall increase is expected mainly in the highlands (Thornton et al. 2006), and Kenyan national staple food production is estimated to decrease overall because of higher evapotranspiration (Herrero et al. 2010). Still, changes in the average annual quantities of rainfall often play a smaller role than changes in variability (Ndehedehe, Agutu, and Okwuashi 2018; Thornton et al. 2014). Agricultural management now requires making both short-term and long-term adjustments to variations in rainfall. In addition to climate variability, land use, especially in the Lake Victoria basin, has been greatly affected by population growth. Since 1970, agriculture has expanded into former grazing land and wetlands, and agricultural land use has intensified on hill slopes that were previously covered by trees (UNEP 2006). More frequent and severe floods and droughts have occurred during the same period (Herrero et al. 2010), partly as a result of land-use changes (Öborn et al. 2015).

Rural services, agricultural advisory services in particular, are often seen as a necessity to reduce farmers' vulnerability to climate-related impacts (Below et al. 2012; Farnworth and Colverson 2015). Kenya's vision for 2030 also proposes adaptation and mitigation options to climate change and variability, including enhancement of farmers' and advisors' knowledge and skills and effective interaction between these (Mohamed et al. 2013). Due to limited positive results from earlier advisory systems in Kenya (Amudavi 2003; Gautam 2000; Niang, Jama, and Nyasimi 2001; Odhiambo et al. 2019), there is a need for more research that can capture positive and negative examples and help the extension system improve its efficiency and impact, including advice on adaptation and mitigation in a socially, economically and environmentally acceptable way (Klein, Schipper, and Dessai 2005). For example, Kenya's current vision for 2030 uses the words 'adaptation' and 'coping' interchangeably

(Mohamed et al. 2013), which could cause confusion and lack of understanding among both advisors and farmers. However, it is important not to narrow down adaptation to knowledge and technology alone (van Aalst, Cannon, and Burton 2008) and to acknowledge that climate variability is just one of the several challenges for smallholder farmers. Smallholders may have the knowledge but not the means to carry out certain adaptation measures. Several earlier studies have called for a better understanding of adaptation awareness and barriers to uptake of adaptation measures among smallholders, especially related to climate (Cavanagh et al. 2017; Deressa et al. 2008; Kalungu and Harris 2013).

Women and men on smallholder farms in sub-Saharan Africa have different roles and different agendas on the farm. Men are more focused on commercial purposes and goals, while women are concerned about subsistence goals to maintain a supply of food, fodder and firewood (Chikoko 2002; Kiptot and Franzel 2011). Men are also generally responsible for property and decision-making and have more time and opportunities to be part of the public sphere (e.g. attending meetings or trainings), when women, on the other hand, are expected to take reproductive responsibility and carry out most of the daily farm work, and are thereby more or less isolated in the domestic sphere (Laszlo Ambjörnsson 2011). Earlier research has documented the imbalances in responsibilities and rights between women and men, although research on agricultural and ecological sustainability rarely takes gender into account (Öborn et al. 2017; Ogunlela and Mukhtar 2009; Rocheleau 1991; Twyman, Muriel, and García 2015).

The overall aim of this study was to identify smallholders' awareness of adaptation and coping measures to rainfall variability, in order to sustain food security and livelihoods, in two contrasting areas in Western Kenya. Specific objectives were to:

(1) Identify smallholders' awareness of adaptation and coping measures to rainfall variability, and examine similarities and differences between women and men farmers' views and between two geographical areas.
(2) Evaluate how access to regular advisory services can affect smallholders' awareness of adaptation and coping measures to rainfall variability.
(3) Identify sources of where farmers learnt the measures from, and recognize factors limiting the use of the measures.

Area background

Study areas

The study was carried out in three (Muhoroni, Nyando and Nyakach) of the seven sub-counties in Kisumu County (Kisumu) and in all five sub-counties in Trans Nzoia County (Trans Nzoia) in Western Kenya (Figure 1) with bimodal rainfall patterns. These two counties have contrasting agricultural conditions in terms of altitude, climate, soils and topography (Online resource 1; Figure 2a,b). Trans Nzoia ('the bread-basket of Kenya') has a cool (mean annual minimum and maximum temperatures of 12°C and 26°C, respectively), wet (mean annual rainfall 1267 mm) climate, due to high altitude (~1800–2000 m above sea level (asl)) and proximity to Mt. Elgon and the Cherangani hills. The cool temperatures allow farmers to harvest just one maize crop that grows during both the long and short rains (Odhiambo et al. 2015). Kisumu, located by the shores of

Figure 1. Map of Kenya (Africa map from Wikimedia commons CC-BY-SA-3.0) showing the two contrasting counties where the study was carried out.

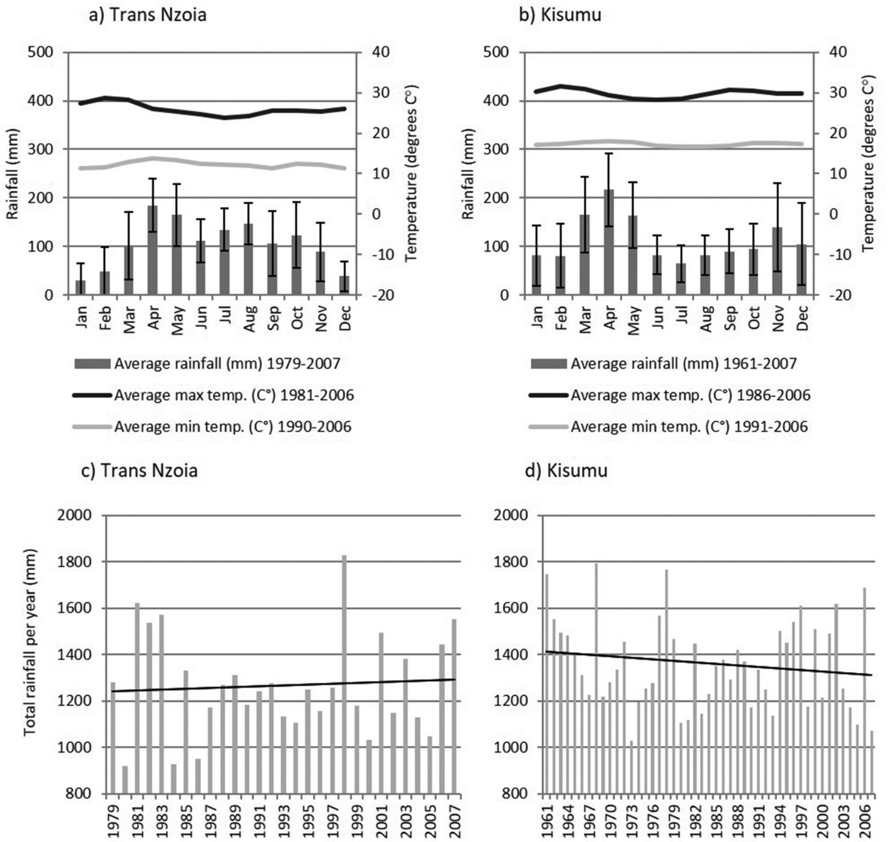

Figure 2. Mean monthly rainfall (± standard deviation) and mean monthly minimum and maximum daily temperatures in periods for which data were available (1961–2007 for Kisumu and 1979–2007 for Trans Nzoia regarding rainfall; 1991–2006 for Kisumu regarding maximum and minimum air temperatures; and 1981–2006 and 1990–2006 for Trans Nzoia regarding maximum and minimum air temperatures) at (a) Kisumu and (b) Trans Nzoia meteorological stations in Kenya. (c) Total annual rainfall 1979–2007 for Trans Nzoia and (d) 1961–2007 for Kisumu (including trendlines).

Lake Victoria, has similar mean annual rainfall (1362 mm), but lower altitude (~1100 m asl) and warmer annual mean minimum and maximum temperatures (17°C and 30°C, respectively). Due to the higher temperatures, farmers in Kisumu can harvest in two maize cropping seasons per year if the rains are favorable (Odhiambo et al. 2015). The inter-annual variability in rainfall is great in both counties, with total annual precipitation ranging between 919 and 1829 mm in Trans Nzoia and 1029 and 1791 mm in Kisumu over a 28- and 44-year period, respectively (Figure 2c,d). In terms of soils, Kisumu is dominated by Vertisols and Planosols that are prone to flooding and overall more challenging for farmers to manage than the Ferralsols in Trans Nzoia (Government 1985).

There are also socio-economic differences between the counties, with mainly one tribe (Luos) in Kisumu and a mix of tribes in Trans Nzoia. Men in the Luo community are traditionally fishermen, although very few pursue this occupation today (Hansen et al. 2011). They inherit their land, where mainly women are engaged in subsistence farming of maize, sorghum, sugarcane, etc. (Bernier et al. 2013; Ocholla-Ayayo 1976). Kisumu town offers job opportunities in the area. The land in Trans Nzoia, on the other hand, is desirable for farming (Otieno, Jayne, and Muyanga 2015), so people from different tribes moved in after colonial large-scale farmers left after independence in 1963. The characteristics of the two areas, with potentially different levels of interest and tradition in agriculture and different preconditions through soils and temperatures, permit interesting comparisons in terms of awareness and limitations of adaptation and coping measures, as agriculture is the main livelihood activity and income source.

Agricultural advisory services in the study areas

Government advisory workers organized within four disciplines (livestock, forestry, agriculture and environment) were present in both areas before or during the study period, together with staff from another government advisory program, the National Agricultural and Livestock Extension Programme (NALEP) (Cuellar et al. 2006). In the Kisumu sub-counties studied, there were 12 government staff (including NALEP staff) in total during the period 2000–2010, while Trans Nzoia had a total of 27 staff in that period (Nyariwo Wilson, personal communication 2014).

A nonprofit and non-government organization (NGO) called Vi Agroforestry also had field advisors in the two counties during the same period. These field advisors offered capacity development in agroforestry and other sustainable management practices, with tree planting by farmers as the core activity (Wekesa and Jönsson 2014). The Kisumu area had five such advisors in total in 2013, but between 2002 and 2010 there were 77. In Trans Nzoia, there were 100–250 advisors between 1990 and 2004, but the scheme was then phased out and it had no advisors by 2013 (Nyariwo Wilson, personal communication 2014). Other NGOs were present in both areas during the study period in 2010, but they were working primarily with HIV/Aids. Both government and NGO advisory services accessed groups rather than individuals, in order to reach more households.

Materials and methods

Selection of participants and set-up of farmer group interviews

The farmer group interviews had the purpose of (i) detecting rainfall-related challenges perceived by farmers, (ii) identifying different adaptation and coping measures that farmers were aware of, (iii) asking farmers to score the effectiveness of measures which they had experience of, on a scale from 0 to 5 (Table 1), (iv) understanding learning sources of measures that farmers had experience from, and (v) recognizing limiting factors when farmers did not practice the measures. The group interviews had a factorial design including the two counties, male and female respondent groups and groups with or without regular access to advisory services. The study had two replicates of each of the eight factorial combinations and thereby 16 groups in total. Advisory service access was divided between farmers who had had regular access to advisory services through the NGO (Vi Agroforestry) during the period 2000–2010, and farmers who had only had occasional contact with agricultural advisors from the government (hereafter called trained and non-trained farmers, respectively). Village elders, local resource persons and field staff from the NGO assisted in informing and calling farmers (almost all were members of formal groups/associations). The participation criteria were that individuals should: (1) represent farm size ≤2.5 ha; (2) obtain the majority (>50%) of their income from the farm; and (3) represent a mix of farms on both flat and sloping land. A short individual questionnaire (Online resource 2) was used to gather some background information on farm size, level of education and extent of market orientation, etc. (Table 2), and to ensure that farmers fulfilled the criteria for participation. After being introduced to the purpose of the study, all participants gave their informed consent for participation. Each group interview had between six and 12 participants (Kumar 1987; McLafferty 2004), who among themselves appointed a secretary to write down all challenges, measures, scores, limiting factors and learning sources on a flip chart for everybody to see, which makes the process more transparent and allows participants to take charge of the discussion to a greater degree (Hay 2010). The farmer group interviews were held in Luo in Kisumu and in Swahili in Trans Nzoia. Questions were standardized across all group interviews and saturation of measures (Hay 2010) was achieved in both counties. A female and male translator was used for women's and men's

Table 1. Full definition of the different scores that could be given to adaptation and coping measures.

Score	Definition of score
0	This measure has **no positive effect** to adapt to or cope with rainfall variability
1	This measure has a **small positive effect**, but alone is **never enough** to adapt to or cope with rainfall variability
2	This measure has a **visible positive effect**, but alone is **rarely enough** to adapt to or cope with rainfall variability
3	This measure has a **visible positive effect** that alone is **sometimes is enough** to adapt to or cope with rainfall variability
4	This measure has a **strong positive effect** and alone can **often be enough** to adapt to or cope with rainfall variability
5	This measure is **enough** alone to adapt to or cope with rainfall variability

Table 2. Background information for all individual participants in the farmer group interviews carried out in Kisumu and Trans Nzoia Counties.

Details of participants	Kisumu (n = 67)	Trans Nzoia (n = 61)	Women (n = 70)	Men (n = 58)	Trained (n = 59)	Non-trained (n = 69)	All (n = 128)
Average age of participants (yrs) (range within brackets)	44 (20–74)	43 (23–84)	40 (20–60)	48 (22–84)	47 (20–84)	40 (22–68)	43 (20–84)
Average family size (no. of persons) (range within brackets)	7 (1–15)	7 (2–17)	7 (1–15)	6 (1–17)	7 (1–17)	7 (1–15)	7 (1–17)
% participants with 0.2 hectares (ha) or less land	21	20	23	17	12	28	20
% participants with more than 0.2 but less than 2 ha of land	78	72	76	74	85	67	75
% participants with 2–2.5 ha of land	1	8	1	9	3	6	5
% participants with no formal education	6	5	9	2	3	7	5
% participants with primary school education	60	61	67	52	56	64	60
% participants with secondary school or higher education	34	34	24	47	41	29	34
% participants with crop products for both consumption and selling	51	82	59	76	64	68	66
% participants with animal products for both consumption and selling	49	66	53	76	59	67	63
% participants with tree products for both consumption and selling	54	64	50	72	63	58	60

groups, respectively. Women were targeted as women farmers, and not necessarily as female heads of households.

The interviews lasted 1–3 hours and were carried out for 2 months in 2010 using a semi-structured interview guide that had been tested on two test farmer groups (Online resource 3) (Hay 2010). All group interviews were audio-recorded and measures were written down by the group secretary on flipcharts. The researcher was listening and taking notes. No transcription or coding was used. During interviews, adaptation measures were referred to as 'measures one plans for', whereas coping measures were referred to as 'measures one may be forced to take'. During data analysis of the interview records, all measures were divided into 11 categories according to their nature and aim, and to the scale at which they are decided upon/practiced (field, farm or landscape).

Statistical analysis

Generalized linear mixed-effect models were fitted to test effects of different factors on: (i) the number of measures identified, (ii) the average score allocated to the measures, and (iii) the number of times different learning sources were mentioned. All analyses were conducted in R 3.4.2, using the glmer function in the lme4 package for tests on the number of measures and the lme function in the nlme package for tests on average score (The R Foundation for Statistical Computing Platform 2017). A first test for farmer groups included the following fixed factors: sex, area (Kisumu vs Trans Nzoia), regular access to training or not, type of measure (adaptation or coping) and the following interactions: type of measure x sex, type of measure x area, type of measure x training. Since each farmer group recorded coping and adaptation measures separately, farmer group was included as a random factor. A separate test was conducted for the scale at which a measure was deployed (field, farm or landscape). For tests of the number of times different learning sources were mentioned by farmer groups, the following fixed factors were used: sex, area, regular access to training or not, and interactions between area x training, area x sex, and trained x sex. Separate tests were conducted for the following learning sources: Elders, Ministry of Agriculture, neighbors and friends, Vi Agroforestry, other sources and common sense (in cases of no external source). For tests on the number of measures, a Poisson error distribution was assumed. However, as over-dispersion was detected, an observation level vector was also added to the random model (Bolker et al. 2009). For tests on average score, a Gaussian error structure was assumed. For each response variable, a model simplification procedure was used to select the model that best explained the variation in the data, by comparing all possible models with the Akaike Information Criterion adjusted for small sample size (AICc). The modavg function in the AICcmodavg package was then used to average all models with ΔAIC <2.0 compared with the best fitting model (lowest AICc value).

Results

Farmers' perceptions of rainfall challenges and awareness of adaptation and coping measures

From the participant background information, it was clear that 94% had some formal education, farm size was small (20% of farmers had less than 0.2 ha) and one-third of the farmers were unable to sell any crop products (Table 2). All farmer groups perceived increasing challenges related to water availability for farming. Too little rain with occasional drought, too much rain with occasional flooding, hailstorms and unpredictable rainfall were the main challenges mentioned in the two areas. Farmers from Kisumu reported that during parts of the year (April–May), heavy rain often led to floods (Table 3). In other parts of the year, those farmers reported a shortage of rain (increasingly erratic) with occasional severe droughts (e.g. from January–March). The farmer groups in Trans Nzoia mentioned increasingly unpredictable seasons, with delayed but more rain during recent years, combined with cold, windy weather with occasional hailstorms.

The 16 farmer groups mentioned between 12 and 40 different adaptation and coping measures each, and a total of 79 different measures were identified (Table 4). Division of these measures into 11 categories depending on their nature and aim revealed that the majority fell within five categories: erosion control, crop production, livestock production, irrigation, and tree production. The other six categories were: off-farm, food and cooking, external, vegetable growing, opportunistic, and other measures. Significantly more (a total of 68) measures (model-averaged estimate: 0.76, 95% CI: 0.5, 1.02) were considered to be adaptation measures than coping measures (11) and the adaptation measures were given significantly higher scores (farmer groups model-averaged estimate: 1.09, 95% CI: 0.66, 1.51) (Figure 3a,b). In all, 33 measures were decided upon and practiced at field level (e.g., ditches, mulching, trees to prevent wind and erosion). Another 25 measures were defined as being decided upon and practiced at farm/household level (e.g. roof catchment, changing eating habits or planting fodder crops). The remaining 21 measures were landscape measures that needed decisions/actions both from the farm and outside the farm (e.g. saving money through a group, selling timber or off-farm income sources).

Many farmers considered coping measures (e.g. selling an animal, tree or sand) to be negative, but necessary for survival (Table 3). Coping measures such as selling labor, eating fewer meals per day and queuing for food aid were considered to undermine farm development, since they caused a decrease in labor for the farm, while many adaptation measures were labor-intensive. On average per farmer group, farmers mentioned similar numbers of measures at farm (9), field (8) and landscape level (7) (Figure 3a). The scores allocated to the effectiveness of the different measures were similar for all farmers, with

Table 3. Citations (translated to English) from the group interviews with farmers from Kisumu (KI) and Trans Nzoia (TN).

Topic	Person	Comment
Rainfall challenges	Non-trained man KI	'Previously we experienced big floods every 10th year (1961–1963, 1971–1972 and 1984), whereas now the floods are more frequent but small floods for a shorter time. Rain used to be constant and reliable nearly every day during the rainy season. Since the beginning of the 80 s, the rain is not reliable and not well distributed. Rain can now come too much in a shorter period and then after that, drought for a longer period.'
Unpredictable rainfall	Trained man in TN	'Before the 60 s and 70 s we knew when rains were coming, but now no-one knows – we cannot predict when or how much rain will come'
Too much rain, wind and hailstorms	Trained man TN	'Too much rain and hailstorms is another problem. Fertilizer can be washed away and extreme cold during that time affects the crops. We have been going back to our old traditional crops that are grown underground like arrowroot, cassava, sweet potatoes and groundnuts, as they are not so much affected by extreme weathers or hailstorms. Use of trees in cropland (agroforestry) also helps when the wind is too strong so that crops are not affected much. It also helps to do dairy farming, as the livestock are not as affected by the weather as crops'
Too much rain	Non-trained men TN	'We concentrate more on livestock during too much rain, since there is not much one can do about the crops. Firewood is a problem during too much rain as we cannot always buy charcoal so sometimes we have food, but we can't eat it raw'
Sell animal as coping measure	Trained woman KI	'How can you sit and watch your livestock die? You just bring it to the market'
Relief food as coping measure	Non-trained men KI	'It has no positive effects', 'the distribution system is corrupt and very selective' and 'even if you get, it will never be enough'
When challenge is too much	Trained woman TN	'We are being forced to be idle'
Drought	Trained woman KI	'When drought is here there is nothing you can do on the farm' and continued talking about different off-farm businesses they carry out instead.
Land for agriculture	Trained man KI	'The subdivision of land has reached a point of no return'
Relevance of fish farming	Trained woman TN	'Fish farming has been promoted by government, but you need much land to put aside some for a fish pond and the pond needs an inlet and an outlet to keep water clean so in these areas where water is stagnant for a long time I don't think fish can do well. Also, some neighbors who tried got problems with the fish pond flooding and fish died or escaped'
Relevance of greenhouse	Trained man TN	'We don't have money to build greenhouses that could protect the crops during both too much and unpredictable rainfall, but they still would be too small to plant maize'
Trees' effect on rain	Trained man TN	'When colonial people were here trees were everywhere and rains were easy to predict, but now trees are cut, and rains are not reliable'
Plant vegetables in a sack	Trained woman in KI	'I always have vegetables and it needs little water'
Less meals per day	Non-trained woman KI	'We work like elephants and eat like hares, get weak and lose weight'
Plant trees and Napier grass on contours	Non-trained woman TN	'It helps a lot since water-flow stops at trees and grass holds the soil'
Leasing land	Non-trained woman TN	'It is often far from your home so people may steal crops and livestock'

Table 4. Adaptation (A) and coping measures (C) identified by farmer groups organized into 11 categories depending on the nature and aim of the measure, and to one of the three different spatial scales, field (FI), farm (FA) or landscape (LA), depending on which level they were decided upon and practiced. Measures mentioned in Kisumu = KI and Trans Nzoia = TN. The number (n) of scorings can be larger than the number of groups since measures were grouped, e.g., there are several types of ditches. Mean and standard deviation (±SD) of scores are shown for single measures where applicable. Farmer groups only scored measures that they had experience from.

Type of measure	Name of measure	A	C	FI	FA	LA	KI	TN	n	Mean score	±SD	Explanation and reason to use measure
Erosion control	Plough/plant along contours								3	5	0	Across slope to improve water infiltration
	Plant without plowing								1	1	-	No tillage to improve water infiltration
	Raised beds								1	5	-	To prevent flooding of crops
	Double digging								1	2	-	To get better root conditions to survive drought
	Dig terraces								2	3	1.4	To promote water infiltration
	Dig ditches								20	2.6	1.4	To promote water infiltration and prevent flooding
	Dig cutoff drain								2	2.5	2.1	Drain ditches to prevent flooding
	Soil in sacks								4	2.5	0.6	Building ridges to prevent flooding
	Grass strips								3	2.6	2.1	Across slope to improve water infiltration
	Stone lines								1	1	-	Across slope to improve water infiltration
	Add mulch								5	2.6	0.9	To promote water infiltration
	Add manure								4	2.75	2.0	To promote water infiltration
	Add compost								1	2	-	To promote water infiltration
	Early plowing								2	1	0	To utilize a shorter rainy season
	Early planting								4	4.25	1.0	To utilize a shorter rainy season
	Dry planting								1	3	-	Plant before rain to utilize a shorter rainy season
	Use greenhouse								10	3.7	1.4	To not depend on rainfall
	TOTAL	17	0	13	4	0	12	14	65			
Crop production	Water-tolerant crops								12	3.4	0.9	E.g., rice, banana, yams, vegetables, sweet potato, cassava
	Drought resistant crops								8	3.75	0.7	E.g., cassava, sweet potato, sorghum, millet, cow/pigeon pea, local vegetables
	Plant under-ground crops								2	5	0	Not affected by hailstorms, e.g., cassava, yams, sweet potato, groundnuts
	Plant traditional crops								2	4.5	0.7	Better adapted to this area, e.g., watermelon, butternut, pumpkin, millet, cow pea
	Plant perennial crops								1	5	-	Can withstand more rainfall variability, e.g., sugarcane, banana, coffee, tea, macadamia
	New/short-term crop varieties								7	2.9	1.2	To be sure to harvest
	Crops in nursery								1	3	-	For survival, then transplant
	Bananas in ditches								1	3	-	To collect water for better performance

(*Continued*)

Table 4. (Continued).

Type of measure	Name of measure	A	C	FI	FA	LA	KI	TN	n	Mean score	±SD	Explanation and reason to use measure
	Plant cover crops								1	4	-	To promote water infiltration, e.g., sweet potatoes, desmodium
	Early harvesting								1	3	-	To get something at least
	Chemical on leaves to reduce moisture								2	3	1.4	Did not know name
	TOTAL	9	2	11	0	0	8	9	38			
Livestock production	Build raised cattle shed								1	5	-	To protect hooves from water when flooding
	Plant fodder								5	4.4	0.5	To not depend on rainfall
	Zero grazing system								1	5	-	To control grazing and improve fodder efficiency
	Dry/store fodder								1	5	-	To not depend on rainfall
	Focus on livestock								10	3.4	1.5	If crops failed, pay more attention to livestock
	Rotational grazing								1	3	-	Graze one area at the time to make grass last
	Beekeeping								4	4	1.4	To not depend on rainfall
	Establish fish pond								6	2.8	1.7	To not depend on rainfall
	Take livestock to greener pasture								3	1.7	1.2	Walk with livestock to other area to graze
	Sell livestock								12	2	0.9	To get money to survive
	TOTAL	9	1	0	8	2	4	9	44			
Irrigation	Pump irrigation								7	3.6	1.9	For crops to survive when drought
	Gravity irrigation								1	5	-	For crops to survive when drought
	Drip irrigation								3	3.7	1.2	For crops to survive when drought
	Hand irrigation								2	3	1.4	For crops to survive when drought
	Dig a water pan								8	2.9	1.5	Small pond to store water
	Roof catchment								8	2.9	1.2	To utilize water better
	Dig a well								2	4.5	0.7	To get water when drought
	Micro-catchments on farm								1	3	-	For improved water infiltration
	Timely watering								1	1	-	Morning and evening to utilize water better
	TOTAL	9	0	5	4	0	8	8	33			
Tree production	Plant trees for erosion control								14	3.4	1.4	To improve water infiltration
	Plant trees for soil fertility								6	3.3	1.3	To improve water infiltration
	Plant trees as windbreak								1	5	-	To prevent strong wind destroying crops
	Plant trees to absorb water								4	3.25	0.5	To prevent flood
	Sell timber								8	1.9	1.0	To get money
	Sell firewood or charcoal								13	2.4	1.3	To get money
	Sell fodder from trees								1	1	-	To get money
	Sell fruit from trees								1	4	-	To get money

(*Continued*)

Table 4. (Continued).

Type of measure	Name of measure	A	C	FI	FA	LA	KI	TN	n	Mean score	±SD	Explanation and reason to use measure
	TOTAL	8	0	4	0	4	3	8	48			
Off-farm	Make and sell baskets, ropes, pots								8	2.4	1.1	To not depend on rainfall
	Make and sell bricks								6	2.8	1.2	To not depend on rainfall
	Keep a shop								7	2.4	1.1	Craftsman, hairdresser, bicycle taxi, shoe polisher
	Go fishing in lake/river								5	3	2	To not depend on rainfall
	Sell labor								13	1.4	0.7	To not depend on rainfall
	Mine and sell stones								4	1.75	1.0	To not depend on rainfall
	Trading								13	2.2	1.2	Buy and sell goods to not depend on rainfall
	TOTAL	4	3	0	0	7	7	4	56			
Food and cooking	Use raised energy-saving stoves								1	5	-	To use less firewood and avoid flooding
	Preserve food								12	4.4	0.7	E.g., with solar dryer to always have food
	Less meals per day								16	1.3	0.7	From three meals to two to make food last
	Change eating habits								6	1.5	0.8	Eat less preferred food to make food last
	TOTAL	2	2	0	4	0	3	4	35			
External	Government dikes								4	4.25	1.5	To prevent flooding
	Relief food								6	1.7	0.5	To survive
	Migration								11	1.2	0.8	To survive
	Help from relatives								1	1	-	To survive
	TOTAL	1	3	0	1	3	4	3	22			
Vegetable growing	Kitchen garden								4	3.75	1.0	Possible to irrigate and have emergency food
	Grow vegetables in a sack								3	3.7	2.3	Possible to irrigate and have emergency food
	Grow tomatoes off-season								1	5	-	To get better price and not depend on rainfall
	TOTAL	3	0	0	3	0	3	0	8			
Opportunistic	Harvest and sell sand								2	2	1.4	Sand comes with water during flooding
	Sell fish from flooded area								1	3	-	Try to fish from flooded area to get money/food
	Sell river water								2	1.5	0.7	To get money
	TOTAL	3	0	0	0	3	3	0	5			
Other	Lease land								2	2	1.4	Plant crops in another place to spread risks
	Saving/loaning/marketing through group								2	2	0	To be able to invest or save for future
	Plant other area								6	2.8	1.7	Swampy, sloping, drier depending on challenge to at least get some harvest
	TOTAL	3	0	0	1	2	3	1	8			
	Grand total	**68**	**11**	**33**	**25**	**21**	**58**	**60**	**364**			

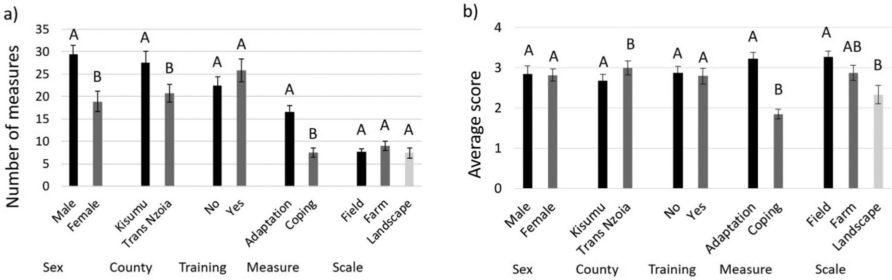

Figure 3. Statistical data on (a) average number of measures (with standard errors) mentioned per farmer group for male and female groups, for groups from Kisumu and Trans Nzoia, for trained and non-trained groups, for measures divided between adaptation and coping measures, and for measures divided between field, farm and landscape-level measures; and (b) average score (Table 1) for the same categories of sex, county, training, measure and scale (with standard errors).

field measures being scored on average highest and landscape measures (mostly coping measures) being scored significantly lower (farmer group estimate: 0.9032, $P < .00$) (Figure 3b). Some farmers complained about the relevance of measures promoted by the government, using deployment of greenhouses as an example since a greenhouse is expensive and only covers a small plot of land, and is therefore insufficient/too risky to rely on (Table 3).

Comparison of the study areas

Similar measures were identified in the two contrasting counties, even though farmers in Kisumu (with higher temperatures, flat topography and soils with slow infiltration) mentioned more extreme rainfall-related challenges and gave significantly lower scores than Trans Nzoia farmers (model-averaged estimate: −0.44, 95% CI: −0.78, −0.11) (Figure 3b). Kisumu farmer groups were aware of significantly more measures (model-averaged estimate: 0.28, 95% CI: 0.08, 0.48), especially on landscape scale, than the farmer groups in Trans Nzoia (Figure 3a). Most of the 21 measures that were only mentioned in Trans Nzoia were related to livestock keeping and tree production, while Kisumu farmers had 19 unique measures mostly relating to opportunistic, off-farm and vegetable growing measures (Table 4). In Kisumu, both men and women mentioned different off-farm opportunities, while in Trans Nzoia it was mainly men. Women in Trans Nzoia even explained that they were “forced to be idle” when rainfall challenges were too great (Table 3). Seventy-one percent of Trans Nzoia farmers had crop, animal or tree products for sale (surplus after consumption requirements), compared with only 51% in Kisumu and the NGO (Vi Agroforestry) was mentioned more than twice as many times as a learning source for a measure in Trans Nzoia (20%) than in Kisumu (8%) (Figure 4). The greatest source of learning measures in Kisumu was elders

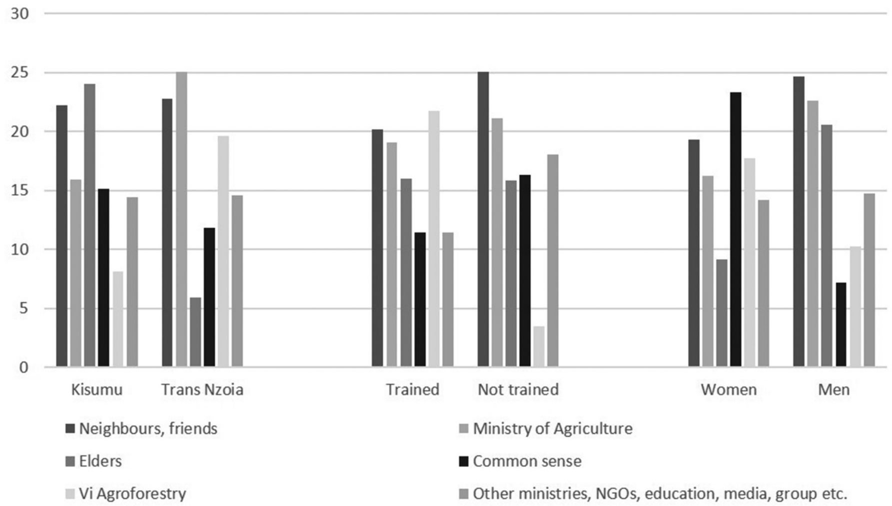

Figure 4. Sources of knowledge for learning about measures (% of all sources) for: men and women, for farmers who were trained and non-trained (regular advisory services or not) and for the two counties.

(24%), a source used significantly more there (model-averaged estimate: 1.58, 95% CI: 0.92, 2.23) than in Trans Nzoia, where only 6% of farmers mentioned elders as a learning source (Figure 4).

Role of gender

Only 24% of the women surveyed had secondary education, compared with 47% of the men (Table 2). Men also learnt significantly more from external learning sources like the Ministry of Agriculture (model-averaged estimate: 0.72, 95% CI: 0.03, 1.41) and elders (model-averaged estimate: 1.16, 95% CI: 0.55, 1.77), compared to women (Figure 4), who relied significantly more on common sense (model-averaged estimate: 0.78, 95% CI: 0.27–1.3). Men identified significantly more measures (29 per group) than women (19 per group) (model-averaged estimate: 0.41, 95% CI: 0.18, 0.65) (Figure 3a). However, they scored the measures similarly (Figure 3b). Women identified mainly field and farm measures (74%), while men were aware of mostly farm and landscape measures (73%). The top three limiting factors to implement a measure were money, knowledge and labor for men, but money, labor and material/tools for women (Figure 5). Moreover, 9% of the men lived on a farm with 2 ha or more land, compared with only 1% of women, and 75% of the men had surplus crop/animal/tree products for sale, compared with just 54% of women.

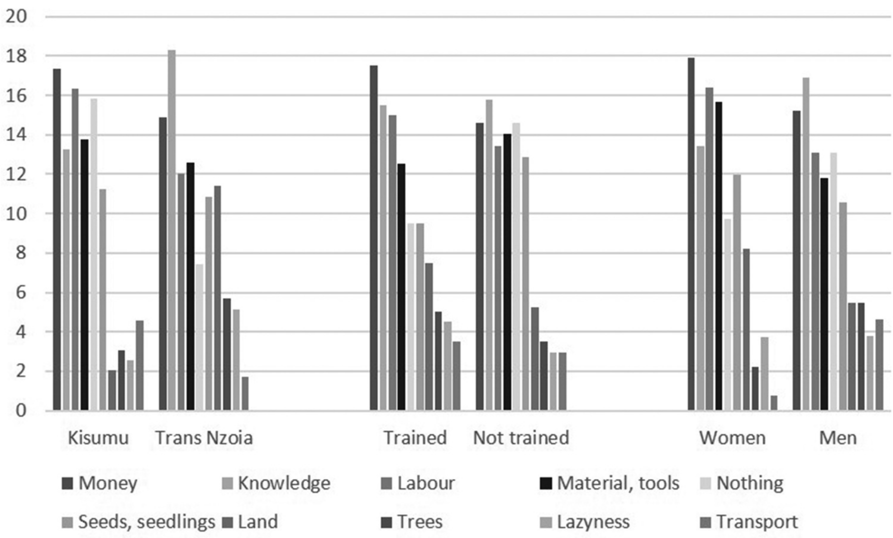

Figure 5. Identified limiting factors preventing farmers from using measures (% of all factors) for: men and women, for farmers who were trained and non-trained (regular advisory services or not) and for the two counties.

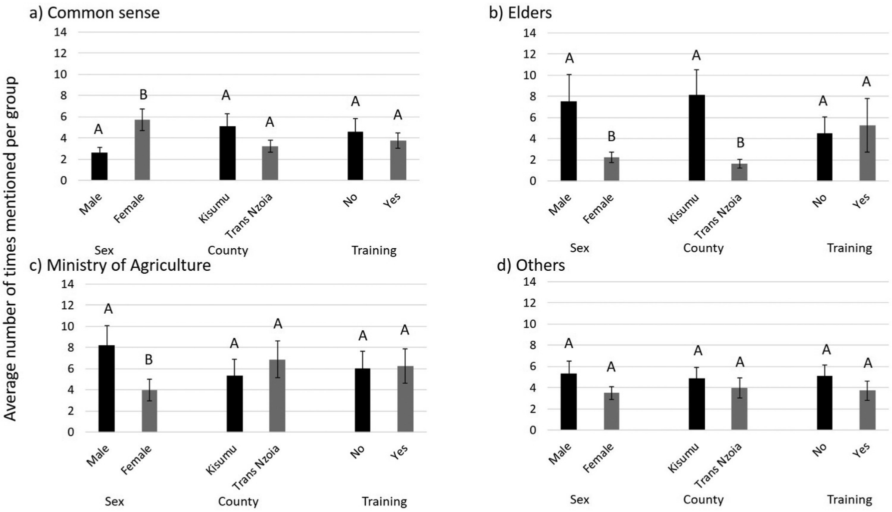

Figure 6. Average number of times a learning source was mentioned per farmer group (with standard errors), comparing men and women, the two counties and trained and non-trained farmers (regular advisory services or not) for: a) common sense (no external learning source), b) elders and relatives, c) Ministry of Agriculture and d) other learning sources (other ministries, other NGOs, education, media or their own farmer group). The remaining learning sources mentioned (neighbors and friends, Vi Agroforestry) were not included, as neighbors and friends did not improve the model fit and Vi Agroforestry was a selection criterion.

Role of access to regular advisory services

Access to regular advisory services did not have a significant effect on the number of adaptation and coping measures farmers were aware of, or the average score of measures (Figure 3a,b). However, there was a tendency for the trained farmer groups to mention more measures with high scores than non-trained farmers, a variable which improved model fit, but was not significant. For example, trained farmers were aware of, on average, four measures relating to trees and three relating to livestock (compared with two and two, respectively, for non-trained groups). Non-trained farmers were aware of more external measures (i.e. measures with external assistance, e.g. relief food), which were scored lower (1.9) than tree (2.7) and animal (3.0) measures in all group interviews. Among trained farmers, 41% had secondary education or higher, compared with only 29% among the non-trained farmers. Trained farmers learnt about 22% of the measures from the NGO, while non-trained farmers instead learned about them from the Ministry of Agriculture, neighbors and common sense (Figure 4b).

Discussion

Inter-annual rainfall variability, changed rainfall patterns or changed land use?

Both female and male farmers taking part in this study reported experiencing challenges related to rainfall variability, as seen among other East African farmers (Adimo et al., 2012; Wetende, Olago, and Ogara 2018). However, several studies in Kenya have also indicated perceived changes in climate, and especially rainfall, among smallholders while the climate data cannot support their perceptions (Bryan et al. 2013; Rao et al. 2011). It can be difficult for farmers to understand the reasons for the increasing challenges, but their experiences are most likely due to a combination of several factors. Perceived changes in rainfall patterns could be directly linked to changes in rainfall amount, intensity and/or interval, but could also be linked to land-use changes (e.g. cultivation of deforested land prone to soil erosion, especially on hill slopes), causing less infiltration, less groundwater recharge and more surface run-off, and thereby temporary floods downslope (Meze-Hausken 2004; Öborn et al. 2015). Moreover, the farmers have become more vulnerable due to factors such as increased population density with agricultural land expansion or smaller farm size as a result (Kebede et al. 2019). Also, a practice of 'growing what you eat', even if cropping is then sometimes pushed beyond suitable areas, with every farmer growing maize instead of traditional, more drought-tolerant crops like sorghum and cassava, could also potentially explain stress perceived as rainfall-related challenges (Deressa, Hassan, and Ringler 2011). Large inter-annual variation (Figure 2c,d) also plays a great role for smallholders in terms of being food secure or not

(Generoso 2015). The large number of adaptation and coping measures mentioned, spanning over eleven different categories and three scales, showed that farmers had a great experience in rainfall variability and its consequences just like was found by Ngugi (2002) and Agesa et al. (2019). The scoring of measures also indicated that no single measure alone can make a household resilient. Rather, the more active choices a farmer can make, the more resilient they become. For example, a combination of food and cash crops can spread the risks. Previous studies have shown the importance of market access (Frelat et al. 2016) and microfinance services (Abate et al. 2016) for smallholders to save and invest in their agriculture and be able to make a profit when trading. Thus, agricultural advisors should be able to facilitate links to these services. Field measures were scored highest and considered to be most effective, probably because the effect was more direct and easy to notice. Some new, innovative adaptation measures were also mentioned (like drip irrigation and greenhouse use), but these need large initial investments.

Farmers clearly explained the drawbacks of the coping measures, giving them significantly lower scores than adaptation measures (Bryan, Theis, and Choufani 2017). A few adaptation measures represented traditional but nowadays rarely used agricultural practices (e.g. preserving food and using drought-resistant, traditional, perennial and root and tuber crops) that have high potential to be successful and sustainable in different combinations (Altieri and Nicholls 2017; Below et al. 2012). The three most limiting factors for implementing adaptation measures according to farmers – money, knowledge and labor – were required in nearly all measures. Access to money and labor sometimes go together, since many farmers have to look for off-farm jobs to sustain themselves, and thereby lose labor for their own farm.

Similar measures in contrasting counties

More extreme rainfall-related challenges like droughts and floods were mentioned, together with a higher number of measures, by farmers in Kisumu, which could be expected owing to that county's higher temperatures and less permeable soils. However, most of the identified adaptation and coping measures were similar between the two counties and reflect findings in other parts of the world (Below et al. 2012; Challinor et al. 2007; Gbegbelegbe et al. 2017; Nguyen et al. 2013). Farmers perceived that better management, e.g. using mulch, having more tolerant/resistant crop types or using different water-saving techniques, sometimes in combination with off-farm businesses, could reduce their vulnerability. Most of the measures mentioned were common agricultural practices designed to improve productivity in general, but which in combination could improve farmers' adaptive capacity (Bedeke et al. 2019; Vermeulen et al. 2012). Vegetable growing, opportunistic and off-farm measures were more commonly mentioned in Kisumu, also by women. This difference is most likely because Kisumu farmers were unable to rely on the farm alone for subsistence (Laszlo Ambjörnsson 2011) and because nearby Lake Victoria and Kisumu town generate more off-farm opportunities. Women in particular, but also men, in Trans Nzoia are thus more vulnerable to extreme weather, since they often lack an off-farm income opportunity (Table 3), which is a common practice for reducing vulnerability (IPCC 2014). In the long term, however, off-farm activities may lead to lost time and labor for their own farms, thereby undermining farmers' future capacity to adapt their own farming to new challenges. Off-farm work also means that farmers actually move away from farming as a way of living, as has happened in Kisumu (sometimes with few viable alternatives of getting food and income), and become dependent on the job market and buying food from other producers, which is being vulnerable in a different way (Challinor et al. 2007).

The NGO, with focus on trees and agroforestry, had been active for longer in Trans Nzoia than in Kisumu, which could be a reason for tree measures being more commonly mentioned in Trans Nzoia. One could expect more adaptation measures in Trans Nzoia, since its farmers were more dedicated to farming and had actively chosen to buy land in a highly productive area (Dulal et al. 2010) relatively recently (after independence 1962). However here, the opposite pattern was found, with more measures identified in Kisumu than in Trans Nzoia (27 and 21, respectively, on average per group), possibly due to a higher need and more severe challenges with rainfall variability in Kisumu (more floods and droughts). Farmers in Kisumu also gave significantly lower scores to the measures (mean 2.7) than farmers in Trans Nzoia (mean 3.0), indicating either that the measures were not working effectively or that a combination of more measures was needed in order to adapt to the more extreme challenges. The two farming counties clearly had different objectives and preconditions for farming. Trans Nzoia farmers had less severe challenges, scored their adaptation measures higher (i.e. rated them more effective) and had more products for sale (crop, animal and tree products). The objective of farmers in Trans Nzoia was really to sustain the family, while in Kisumu the farm was sometimes more of a security behind other income-generating activities. It was more common in Kisumu to learn adaptation and coping measures from elders, while in Trans Nzoia a higher percentage of farmers learnt from the NGO (Figure 4b). There could be at least two reasons for this difference: the NGO had worked longer in Trans Nzoia than in Kisumu, and farmers in Trans Nzoia had migrated from other areas and therefore had fewer elders around to learn from.

Men get the training and women do the farming

The reasons why women identified less adaptation and coping measures, just like in another Kenyan study (Kalungu and Leal Filho 2018), are probably multiple and complex, involving legal rights, traditions and cultural taboos, which commonly affect women negatively (Doss 2001). For example, women identified fewer tree production measures, but since trees are more permanent on the farm and planting/cutting needs a decision from the land owner (the man), women might feel demotivated to engage in tree-related measures (Kiptot and Franzel 2011). Women had less products for sale and listed fewer livestock-keeping measures, potentially since money and animals (except chickens) are mostly men's responsibility (Andersson and Gabrielsson 2012). In addition, women had smaller farms, less education and were less exposed to different external learning sources, which is similar to the situation in other sub-Saharan African countries (Doss and Morris 2000; Felix et al. 2010). This illustrates the vulnerable condition of female smallholders, not only bio-physically but also in relation to human and institutional capacity (Diiro et al. 2018; Dixon, Smith, and Guill 2003). It means that women have to rely more on 'common sense' to learn new measures, probably because they mostly do domestic work on the farm and in the household, and thereby rarely travel to trainings, meetings or advisory offices (Kiptot and Franzel 2011). However, the women in this study had learnt measures from the NGO to a larger extent than the men, which suggests its advisory services were efficiently aimed and actually reached women. Women did not feel as limited by knowledge as men, perhaps since women had a lot of experience of challenges in farming, and very limited experience of education and training. The fact that women commonly remain within the domestic sphere and carry out much of the actual farm work can explain why they identified fewer landscape-scale measures than men.

For women to improve their adaptive capacity, they need to get better access to education and training in general and advisory services in particular, but also access to land and capital, i.e. property and power (Diiro et al. 2018; Doss and Morris 2000; Gabrielsson and Ramasar 2013). These system changes take time, but one important start could be policies and laws. Here, the Kenya Vision 2030 has a great role to play and could set the standard. Kenya Vision 2030 states that women and men should be treated equally and that women should have increased participation in economic, social and political decisions (Kenya 2007). It also highlights the importance of raising public gender awareness (Mohamed et al. 2013). However, the examples given are to have more women in parliament and more money in the women's enterprise fund (Kenya 2007) which, while good initiatives, may not have much impact for smallholders in rural areas. The national climate change action plan (part of Kenya Vision 2030) mentions gender discrimination of women and describes women as a particularly vulnerable group in terms of climate change impacts and rainfall variability (Mohamed et al. 2013). This indicates that women need to be specially targeted with such examples as agricultural advisory services, education opportunities, land rights' information, and microfinance services, so that over time they are able to utilize a demand-driven service system on equal terms to other farmers.

Advisory services affect types of measures

The relationship between better adaptive capacity and smallholders having regular access to advisory services reported in other studies (Below et al. 2012; Deressa et al. 2009; Yang et al. 2017) was not supported by findings in this study. However, farmers accessing regular advisory services tended to be aware of more, and especially more effective, measures according to their own scoring, such as agroforestry, mulching and water harvesting (Figure 3a). These measures are triple-win measures that can potentially mitigate emissions, improve adaptation capacity and increase profitability (Bryan et al. 2013). Such measures are highly relevant, both according to Kenya's national strategy (Mohamed et al. 2013) and the worldwide focus on climate-smart agriculture (FAO 2015). However, according to Speranza et al. (2010), such practices are becoming less common for socio-economic or socio-political reasons, due to limited capital and labor or insecure land tenure, which together with knowledge were also among the most limiting factors in this study.

Farmers with regular advisory services tended to have higher educational background, and fewer had farm sizes below 0.2 ha, compared to farmers without regular advisory services, which could be why the former tended to know more measures. However, it could also mean that the more educated farmers were more actively seeking new knowledge, joining group training and adopting measures, which can relate to the challenge of reaching the poorest of the poor with information (Gwatkin, Wagstaff, and Yazbeck 2005; Karanja Ng'ang'a, Jalang'o, and Girvetz 2019; Lønborg and Rasmussen 2014). Also, the 'gap' identified (by farmers) between farmers and advisors needs to be reduced. One option could be to strengthen the horizontal sharing and learning of methods where farmers are leading the process through their own groups and associations (Rosset and Martínez-Torres 2012). Farmer-to-farmer learning networks have been successfully implemented elsewhere to overcome social barriers and to be able to scale up measures for an improved sustainability and resilience among smallholders (Rosset et al. 2011).

Conclusions

Smallholders in Western Kenya perceived and described increasing challenges relating to rainfall variability that made them feel vulnerable. While it was not possible to disentangle the causes of this increased vulnerability, the need for adaptation measures was obvious. Smallholders were knowledgeable and creative in terms of adaptation measures at field, farm and landscape scale that, in a sustainable way, could help them adapt to rainfall variability challenges. However, natural capital (rainfall) was not their only challenge, as human (labor), social (knowledge) and produced (money) capital were all limiting the farmers from adaptation work. When adaptation measures were not sufficient to manage a challenge, farmers knew different coping measures for survival, although coping measures often lead to negative consequences for farming.

Direct measures at the field level were considered most effective followed by measures at the farm/household level, while landscape-scale measures that involved another stakeholder than the farmer were rated lowest. Kisumu experienced more severe challenges and had greater awareness of both adaptation and coping measures, even though adaptation measures were scored less effective in Kisumu compared to in Trans Nzoia. Households in Kisumu often had off-farm income sources to reduce their dependence on farming, while farmers in Trans Nzoia mainly lived from farming.

Access to advisory services seemed important but was not a significant factor for adaptation measures. Women knew less measures than men and had least opportunities for training and education. This calls for more structural changes, as outlined in the national climate change action plan as part of Kenya Vision 2030. Further research is needed on the roles of women and men in smallholder farming and their access to and engagement in different advisory services approaches, and its connection to the actual use and effectiveness of different adaptation and coping measures on food security, livelihood and resilience.

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Disclosure statement and compliance with ethical standards

No potential conflict of interest was reported by the authors. All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments, or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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The role of trees and livestock in ecosystem service provision and farm priorities on smallholder farms in the Rift Valley, Kenya

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ABSTRACT

Human beings are dependent on ecosystems and the services they provide. Some services are currently being overexploited, resulting in degradation and further pressure on already vulnerable people in e.g., sub-Saharan Africa. Long-term and stable delivery of ecosystem services (ES) is suggested to be enhanced by more diversified farming systems that e.g., mix crops with trees and livestock. Despite the amount of research on ES, few previous studies have identified and compared the roles of trees and livestock for ES considering farm priorities within smallholder systems. We studied the role of trees and livestock for ES provision as well as farm priorities for smallholders in Kenya. Twenty smallholder farms (0.2–0.8 ha) were studied for 1 year in a fully factorial design of high or low tree and livestock density systems. Data were collected on indicators for provisioning (crop, tree and livestock production), supporting/regulating (water infiltration, soil organic carbon and nutrients) and cultural (recreation and aesthetics) ESs. In addition, farm priorities were studied, considering nutrient management, on- and off-farm resources, food and consumption, and crop, tree and livestock species diversity. A mix of qualitative (e.g., semi-structured interviews, seasonal calendar) and quantitative (e.g., soil analyses, infiltration tests) methods were used to collect data. This study confirmed roles of trees and livestock for ES and farm priorities, although they in some cases appeared less important than family labour and farm size. Results showed that high tree density was related to higher workload, lower proportions of off-farm revenue as well as higher crop, fruit and tree diversity for the household. Tree or livestock density showed no clear relation to provisioning, supporting or regulating ES. However, cultural services were on average provided more by trees than livestock. Available family labour was positively related to both farm production (provisioning services) and crop, tree and livestock species diversity. The use of manure, compost and mineral fertilisers was overall low, and the application rate per unit area seemed higher on farms with less land which was reflected in higher soil P and Ca concentrations. The challenges of already small and reducing farm sizes need to be targeted seriously in research and development efforts. Also the issue of labour requirement and pathways for mechanization must be addressed to attract a new generation farmers to develop sustainable and profitable farm enterprises providing ES to the farm and the surrounding landscape.

1. Introduction

Humans are completely dependent on ecosystems and the services they provide. Some important services are being over-exploited, resulting in degradation of ecosystem services (ES). This is particularly problematic for people who are already vulnerable, e.g., smallholders in developing regions such as sub-Saharan Africa (Allen et al., 2018). In the Millennium Ecosystem Assessment (MA, 2005), ES are divided into provisioning (e.g., food and fuel), supporting (e.g., nutrient and water cycling), regulating (e.g., water and disease regulation), and cultural (e.g., aesthetics and recreation) services, which can be quantified using indicators (Hernández-Morcillo et al., 2013; Kearney et al., 2017; Kragt and Robertson, 2014). It has been suggested that long-term and stable delivery of ES can be enhanced by more diversified farming systems that e.g., mix crops with trees and livestock (Erisman et al., 2016; Kahane et al., 2013; Kuyah et al., 2016; Vandermeer et al., 1998).

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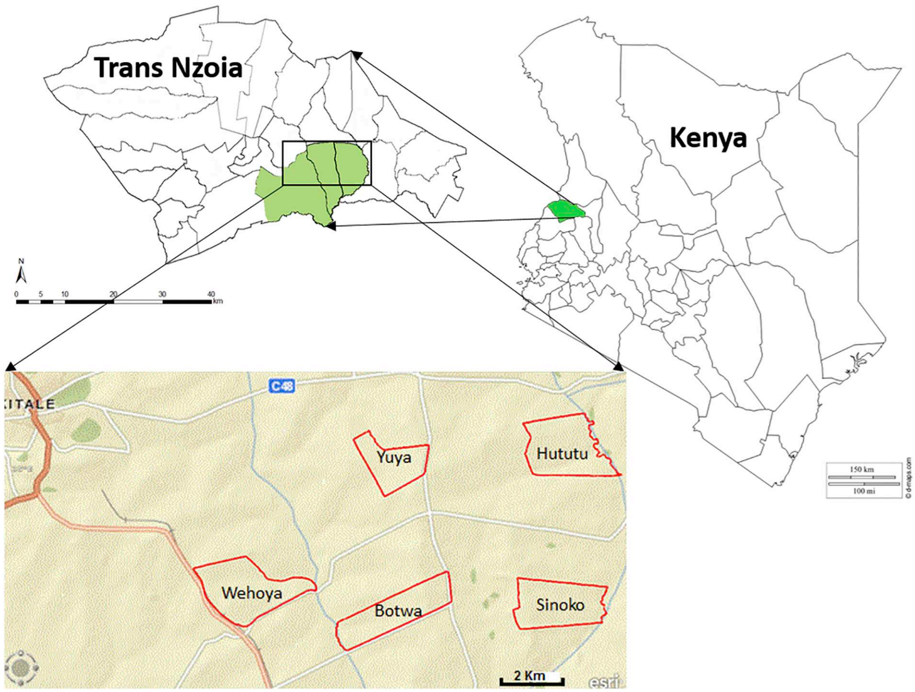

Fig. 1. Map showing the five settlements selected for this research study in Trans Nzoia County, Rift Valley, Kenya (modified with permission from Nyaga et al., 2015).

However, there are trade-offs between several farm management practices, often between short-term gains and long-term stability (Tittonell et al., 2011).

East Africa is the most densely populated part of sub-Saharan Africa and soils and agricultural landscapes in this region are becoming increasingly degraded (Blake et al., 2018). In these areas, research has indicated that in addition to maintaining diversified farming systems, improving the soil organic carbon (SOC) content on farms is key for restoring ES (Foley et al., 2005). Nutrient cycling plays an essential role in restoring soil fertility and here livestock can be important contributors to several ES services through recycling of nutrients and improving soil structure (Agegnehu and Amede, 2017; Henderson et al., 2016; Nowak et al., 2015; Pagliai et al., 2004). Recent studies also recommend that priority is given to having more trees on farms, which can also contribute to several ES (Kuyah et al., 2016; Lohbeck et al., 2018; Mutabazi et al., 2015). Mixing different species of crops, trees and livestock on farm can provide a variety of ES which potentially help to buffer the farming system against perturbations (Cabell and Oelofse, 2012; Erisman et al., 2016). Farmers have different priorities and often want to produce a variety of products and services on their farm. Crops are mainly grown for home consumption or sales, while trees and livestock have an additional role as providing insurance, i.e., when challenges arise, a tree or livestock can be sold to get fast cash (van der Ploeg et al., 2009). However, farmers often prefer livestock over trees as insurance and some claim that the benefits from livestock are necessary for farmers to invest in trees or agroforestry (Jerneck and Olsson, 2013). Trees and livestock are known to generate several ES including provisioning, supporting, regulating, and cultural (Henderson et al., 2016; Rönnbäck et al., 2007). However, both trees and livestock can potentially compete with crop resources (land, water, nutrients, labour) on farm. Therefore, their separate roles in delivering ES needs further research and quantification (Mutoko et al., 2015).

Soil organic matter affects several ES (Kearney et al., 2017). In addition, the use of organic fertilisers can both increase crop yields and decrease yield variability and thereby improve household resilience (Chen et al., 2018). Resilience is here defined as the disturbance a system can withstand without changing its functions (Folke, 2006). Both trees and livestock can potentially add organic material to the soil in the form of manure or litter, with positive effects on soil fertility and soil structure (Altieri and Nicholls, 2017). However, for smallholders the trade-offs in the use of crop residues and other types of organic material between e.g., mulch, fodder and fuel are challenging, just like trade-offs in other management aspects (Tittonell et al., 2015; Turmel et al., 2015). Drivers of change in farming systems and their management are both complex and vary between households, times and places. Therefore, it is important to consider variables which represent farm priorities and can indicate important linkages and trade-offs between ES and the relation to farm resources (Kebede et al., 2019). Available labour and farm size have been found to be two important resources that can drive changes in farm management (Dahlin and Rusinamhodzi, 2019; Muyanga and Jayne, 2014).

Building more sustainable farming systems requires a broad research approach which incorporates both social and ecological aspects (Cabell and Oelofse, 2012). Despite the amount of research on ES, and a general understanding that higher diversity within systems can lead to more sustainable development (Blicharska et al., 2019; Finney and Kaye, 2017; Isbell et al., 2017), few previous studies have identified and compared the roles of trees and livestock for ES considering farm

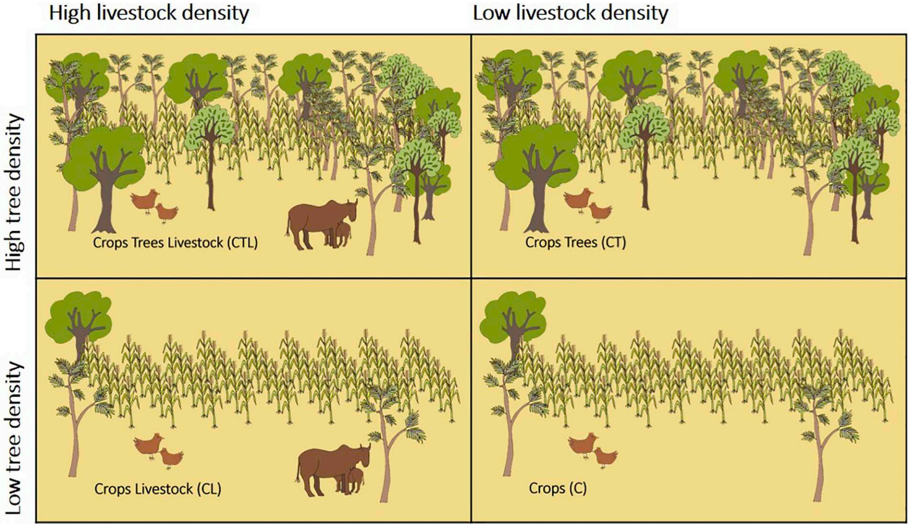

Fig. 2. Illustration of study farms selected to have either high or low tree and livestock density, in combinations with crops: Crop-tree-livestock farms (CTL) have high tree density and high livestock density including cattle; crop-tree farms (CT) have high tree density and low livestock density excluding cattle; crop-livestock farms (CL) have low tree density and high livestock density including cattle; and crop farms (C) have low tree density and low livestock density excluding cattle (illustration by Ylva Nyberg).

(1982) where 250 kg = 1 = water buffalo, adult cattle = 0.7, calf = 0.4, sheep/goat = 0.1, hen/dove = 0.01, dogs and cats excluded.

2.3. Choice of indicators for ecosystem services

Since ES is a wide concept and difficult to evaluate and compare between different studies (Egoh et al., 2012), several indicators for the same services were analyzed in this study (Supplementary Table 1). Crop yields of maize and beans, and farm production of firewood, fruit, eggs, and milk, were chosen to represent provisioning services. Crop yield is a commonly used indicator of provisioning services (Egoh et al., 2012). Farm products of crops, livestock and trees in monetary value per hectare (ha) land was also used as a provisioning service indicator (exchange rate of 1 KES = 0.01 USD). For each of crop, livestock and tree production, the annual return on investment (ROI, Eq. (1)) was calculated as:

$$\text{ROI} = \text{Profit}/\text{Investments} \quad (1)$$

where profit = revenues – investments (Friedlob and Plewa Jr, 1996).

Indicators for supporting services, included percentage of total soil carbon (here assumed to be equal to SOC), total soil carbon/nitrogen (C/N) ratio, available phosphorus (P), calcium (Ca), magnesium (Mg) and potassium (K) levels, and soil pH (Supplementary Table 1). The indicators used for soil structure maintenance, a regulating service, were topsoil bulk density and water infiltration capacity, which can be associated directly with water retention, one of the most frequently assessed services in the literature (Feld et al., 2009).

Cultural services provided by having crops, trees, and livestock were analyzed, as was the presence of ornamental plants (Supplementary Table 1). Indicators of the proportions of tree and livestock species on a farm used for cultural (e.g., recreational or aesthetic), services were calculated. Proportions were used to overcome the fact that number of trees was a selection criterion for the farms, although actual numbers of trees were also included as an indicator.

2.4. Choice of key variables representing different farm priorities

To understand the prioritizations made by farmers in general and especially in relation to livestock and trees, categories such as nutrient management, on- and off-farm resources, food and consumption and species diversity were considered (Supplementary Table 2). Key variables for nutrient management included annual application of organic and inorganic amendments and the proportion of maize residues returned to the fields (either left in situ or composted and returned) or fed to livestock. The category of on- and off-farm resources included several key variables that have been identified and used in earlier research related to the balance of on- and off-farm revenue (Ifejika Speranza et al., 2014; Kebede et al., 2019). The key variables were land per capita, average person-hours spent on farm work per day, total and proportion of total revenue earned off-farm (Supplementary Table 2).

Food and consumption was considered as another relevant category since more than 20% of the sub-Saharan African population have a diet with enough calories but lacking essential vitamins, minerals, and protein (Kahane et al., 2013). Milk and fruits are important sources of vitamins and protein, however, not always affordable for poor people (Kahane et al., 2013). Milk and fruit intake were therefore chosen as key variables together with the proportion of total food consumed which is purchased and proportion of revenue used to buy food.

Species diversity for crops, trees and livestock can be related to resilience. When there is a drought, some crops may die and others survive and therefore a large number of crop species can be used as an indicator of resilience in agriculture (Mutabazi et al., 2015). Numbers of crop, livestock, and tree species were included as key variables together with the Shannon diversity index for trees, which combines species richness and evenness (Shannon and Weaver, 1949). The Shannon diversity index (H, Eq. (2)) is calculated as:

$$H = (-1) * ((p_1 * \ln(p_1)) + (p_2 * \ln(p_2)) + \ldots + (p_n * \ln(p_n))) \quad (2)$$

where p is the proportion of each specie and n is the number of species (Shannon and Weaver, 1949).

2.5. Semi-structured interviews with farm households and crop, livestock, and tree inventory

Crop yields, farm production and farm management data (e.g., on use of soil amendments) were collected using semi-structured interviews in combination with the Participatory Rural Appraisal (PRA) seasonal calendar tool (Cavestro, 2003). During farm visits at the beginning of the project, an inventory was also carried out for each household, in order to assess the crop, tree, and livestock densities and species diversities.

In order to track flows of revenues and expenditures per household, farmers were encouraged to participate in record keeping, especially of economic flows within, to, and from the farm. Farmers were given forms to fill in that were checked and updated during monthly farm visits throughout the year. Some farmers were not able to fill in the forms themselves and were instead interviewed when visited and sometimes phoned for updates, questions, and/or to clarify irregularities. The same field assistant and interpreter were involved during the whole annual cycle of field work.

2.6. Soil sampling for bulk density, carbon and soil nitrogen, phosphorus, and potassium

Three topsoil bulk density cores were collected in the maize/bean field, dried, and weighed for bulk density calculations, and a farm average was determined. Topsoil (0–15 cm depth) was sampled in the largest maize/bean field, the homestead, and in two to four more fields. The topsoil was systematically collected as a composite sample with 20–40 subsamples from at least two crop rows, depending on the field size. The soil samples were analyzed for soil pH ($CaCl_2$), SOC, total nitrogen (N) and extractable plant nutrients. Total SOC and N were analyzed (CNS 2000 dry combustion analyzer), and the C/N ratio was calculated. Extractable P, K, Mg, and Ca were determined by Mehlich 3 extraction (Mehlich, 1984), followed by element analysis using atomic emission spectrometry (ICP). Farm averages were calculated for all elements.

2.7. Double-ring water infiltration tests

To determine the water infiltration rate, double-ring tests were used (Brady and Weil, 2002). For this, two metal rings (20 and 30 cm diameter) were pressed around 5 cm into the soil. Water was poured into the inner ring and between the rings, to measure the infiltration rate in the inner ring while preventing water moving horizontally in the soil. Measurements continued until the rate was stable. Six double-ring tests were carried out in the maize/bean field on every farm and farm mean infiltration rate was used in further data analysis.

2.8. Data preparation and statistical analysis

All indicators and key variables (Supplementary Tables 1 and 2) were response variables in statistical analyses using the lm function in R 3.4.2 (R Core Team, 2019). The linear model was based on the fully factorial design with high and low tree and livestock density and their interactions. Farm size (ha) and family labour (available number of persons) were added as co-variates. Adults (18 years and above) were counted as one person and children (below 18 years) were counted as half a person since children also contribute in terms of labour. These factors were added both in order to see any effects of farm size and family labour as well as to make sure that the potential effects of tree or livestock density were based on average farm size and family labour availability. A factor for settlements (blocks) was added after the co-variates and before the other factors. In the significant interaction between tree density and livestock density, a comparison of all combinations/farm types (crop-tree-livestock; crop-livestock; crop-tree; crop) was carried out using the compact letter display function in the multcompview package. These pairwise *t*-tests were adjusted for multiple comparisons using Tukey's method to determine any significant differences. Throughout the analyses, gaussian distributions were expected, though in some cases log-transformations were necessary. However, ES indicators or farm priority key variables that were based on proportions were logit transformed before analyses to fulfill assumptions of the parametric test. The logit transformation (Eq. (3)) was calculated as:

$$z = \ln(p/(1 - p)) \tag{3}$$

where z = logit value and p = proportion (Welham et al., 2014). The significance level was set to $P < .05$. Standardized *Z*-scores were used to compare all indicators and variables for the different farm types in radar diagrams. Z-scores (Eq. (4)) were calculated as:

$$Z = (x - \mu)/\sigma \tag{4}$$

where Z is the Z-score, x is the data point, μ is the overall mean and σ is the standard deviation (Geher and Hall, 2014). If a Z-score is zero, it indicates that the data point's score is identical to the mean score. A correlation matrix was also prepared, to examine potential correlations among soil properties.

3. Results

3.1. Ecosystem service indicators and farm priorities

When considering an overview of the indicators (Fig. 3), the provisioning ES seemed to vary in relation to the selection criteria with trends of more tree products for high tree density farms and more milk production for high livestock density farms. Crop farms showed patterns of higher egg production and farms with low livestock density seemed to have higher bean yields. Supporting and regulating ES indicators varied least but low livestock density farms showed patterns of higher C/N ratio and higher P and K for CL farms. Patterns for farm priority key variables showed that crop farms seemed to rely more on off-farm revenue than other farms (Fig. 3). CTL farms tended to spend more person-hours on farm work. Some of the variation in ES between farms could be explained by the co-variates (Table 2, Fig. 3). The first analyses showed a closer connection between ES and the co-variates (family labour and farm size) than to tree and livestock density. Further, the actual livestock density (in TLU ha^{-1}) and tree density were found not to correlate with any of farm size or family labour.

3.2. Provisioning services

The farm average production among the high or low tree and livestock density farms ranged between 1687 and 2208 kg ha^{-1} for maize and 77–183 kg ha^{-1} for beans (Table 2). Firewood farm average production over 12 months was 14,000 KES with high tree density and 700 KES with low tree density. Similarly the farm average milk production varied greatly from 3000 KES to 21,000 KES for those with low and high livestock density respectively. Fruit and egg production per household varied less and ranged between 3000–7000 KES for fruits and 160–315 eggs on average. The total value of all crop, livestock and tree production was similar between high tree and high livestock density with a farm average of 268,000 KES compared to 180,000 KES for farms with low tree or low livestock density. Tree or livestock density was however not significantly associated with the studied provisioning services including crop production (maize, common beans), firewood, fruits, eggs, milk or total farm production. Family labour was instead found to have positive associations with fruit ($P = .01$), milk ($P = .04$) and total farm production ($P = .04$) (Fig. 4a–c, Table 2), whereas farm size was not related to crop, tree or livestock provisioning services. Comparing the three farm components (crops, livestock, trees) more closely revealed that the annual ROI (Eq. (1)) varied widely between components and between farm types (Fig. 4d). Livestock had a ROI

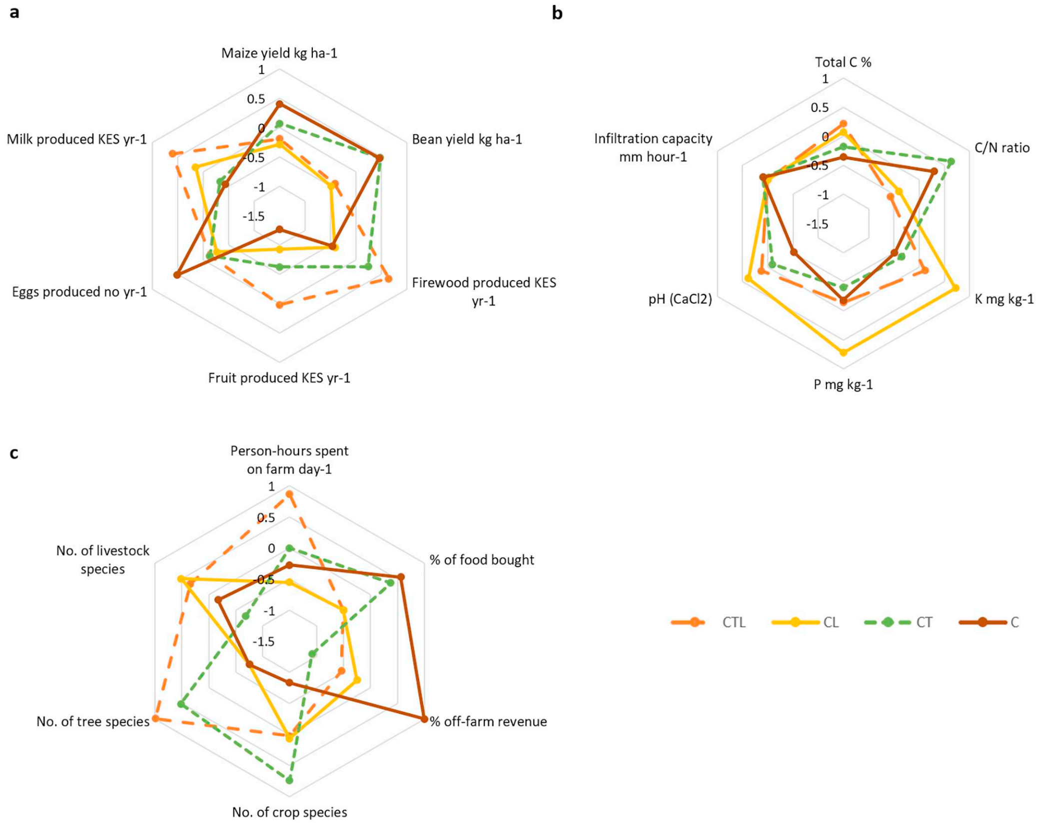

Fig. 3. Indicators of ecosystem services (ES) and key variables of farm priorities, represented as standardized *Z*-scores (Eq. (4)) for the high or low tree and livestock density farms (Fig. 2) in radar diagrams including selected a) provisioning ES – farm products, b) supporting and regulating ES – represented by water infiltration capacity of the soil and soil characteristics important for soil fertility; total soil organic carbon (SOC), total carbon – nitrogen (N) ratio (C/N ratio), soil acidity (pH), available plant nutrients – phosphorus (P) and potassium (K) and c) farm priorities in terms of on and off-farm resources, food variables and species diversity – represented by daily person-hours spent on farm-work and proportions of purchased food and off-farm revenues, as well as numbers of crop, tree and livestock species. Crop-tree-livestock farms (CTL) were selected to have high tree and livestock density; crop-tree farms (CT) to have high tree and low livestock density; crop-livestock farms (CL) to have low tree and high livestock density; and crop farms (C) to have low tree and livestock density.

ranging between 0.6 and 6, crops had ROI between 3.4 and 8.3 and varied the least between the farm types. Trees had the highest variation with ROI between 1.3 and 48. Due to the longer rotation time for livestock and especially trees, compared to crops, the annual ROI can vary considerably between the years depending on the stage of production within the rotation cycle.

3.3. Supporting and regulating services

No significant associations were found between the two experimental factors, livestock and tree density, and the selected soil parameters used as indicators for supporting and regulating ES (Table 2). However, some of the soil quality ES indicators had a significant relation with farm size where higher concentrations of available soil P ($P = .008$) and Ca ($P = .04$) and a higher soil pH ($P = .02$) was found on smaller farms (Fig. 5a,b). Labour was not associated with any of the supporting and regulating ES indicators. Settlements, used as blocks in the statistical analysis, differed significantly in SOC content and water infiltration capacity ($P = .02$ respectively $P = .002$) with Yuya having the highest levels (Table 2).

3.4. Cultural services

On average 3–6 tree species per farm had roles in terms of beauty or recreation with both low and high tree density. A larger proportion ($P = .001$) of tree species (average 54%) therefore provided cultural services on low tree density farms compared with on average 7% on high tree density farms (Table 2). The most common reasons for planting trees were to produce fruit, firewood, timber, shade, and medicine. However, on low tree density farms, the cultural services (especially shade for recreation) had a high priority since more than half of the trees were used for cultural services on these farms. Some farmers also talked about planting trees to bring rain (assumed as a regulating service) or to get good sticks for herding cows or poles to hold bananas, or because of high demand for the seeds (provisioning services). Some traditional meanings of certain tree species were

Table 2
Selected ecosystem services' indicators (mean and 95% confidence intervals (CI)) for the study farms with high or low tree and livestock density (n = 20).

No	Indicators and units (farm average unless stated)	Low tree density	High tree density	Low livestock density	High livestock density	Significant results
		Mean (95% CI)[a]	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)	
	Provisioning ecosystem services					
1	Maize yield (kg ha^{-1})	2013 (1386–2640)	1882 (1255–2509)	2208 (1570–2845)	1687 (1050–2324)	
2	Bean yield (kg ha^{-1})	98 (46–209)	143 (67–305)	183 (86–395)	77 (36–164)	
3	Firewood produced, 1000 KES yr^{-1}	0.7 (0 − 11)	14 (3–24)	6 (0–16)	9 (0–19)	
4	Fruits produced, 1000 KES yr^{-1}	3 (0–8)	7 (2 − 12)	4 (0–9)	6 (1 − 11)	B P = .01 +
5	Eggs produced, no yr^{-1}	289 (0–619)	187 (0–518)	315 (0–652)	160 (0–496)	
6	Milk produced, 1000 KES yr^{-1}	9 (0 − 22)	16 (2–29)	3 (0–17)	21 (8–34)	B P = .04 +
7	Total value of produce (crop, livestock, tree) ha^{-1} yr^{-1} (1000 KES)	180 (121–268)	268 (180–400)	180 (121–268)	268 (180–400)	B P = .04 +
	Supporting/Regulating ecosystem services					
8	% total soil organic carbon (SOC)	1.78 (1.64–1.95)	1.83 (1.70–1.98)	1.76 (1.61–1.91)	1.87 (1.71–2.02)	S P = .02
9	C/N ratio (soil carbon:nitrogen ratio)	13.9 (13.6–14.3)	14.0 (13.6–14.3)	14.2 (13.8–14.6)	13.7 (13.3–14.0)	
10	Available P (mg kg^{-1})	32 (22–43)	20 (10 − 31)	20 (9–31)	33 (22–44)	F P = .008 −
11	Available K (mg kg^{-1})	405 (296–513)	365 (257–473)	313 (203–423)	457 (347–567)	
12	Available Mg (mg kg^{-1})	183 (146–220)	182 (145–219)	159 (122–197)	206 (168–244)	
13	Available Ca (mg kg^{-1})	853 (715–990)	921 (783–1058)	822 (682–961)	952 (812–1092)	F P = .04 −
14	pH ($CaCl_2$)	5.14 (4.95–5.33)	5.17 (4.98–5.37)	5.06 (4.87–5.26)	5.25 (5.05–5.45)	F P = .02 −
15	Bulk density (g cm^{-3}) in maize/bean field	1.16 (1.08–1.25)	1.19 (1.11–1.28)	1.17 (1.09–1.26)	1.19 (1.10–1.27)	
16	Infiltration capacity in maize/bean field (mm $hour^{-1}$)	277 (248–306)	276 (247–305)	279 (250–308)	274 (245–304)	S P = .002
	Cultural ecosystem services					
17	% of livestock species used for some cultural services	2.2 (0.7–6.8)	1.8 (0.6–5.6)	3.9 (1.2–11.8)	1.0 (0.3–3.3)	
18	% of tree species used for some cultural service	54 (32–75)	7 (3–16)	28 (13–50)	19 (8–37)	T P = .001 −
19	No of tree species used for some cultural service	3 (3–4)	6 (6–7)	5 (4–5)	5 (4–5)	
20	No of farms with ornamental plants	8	10	10	8	

Indicators measured in percentages were logit transformed (Eq. (3)). Significant results in the last column are based on associations (positive with + and negative with −) the factors of settlement (S), tree density (T) and livestock density (L) as well as the co-variates of farm size (F) and family labour (B) in a linear model.
[a] In case confidence intervals included negative values, they were adjusted to 0.

mentioned by four farmers as reasons to plant them. *Markhamia lutea* was believed to prevent people from quarrelling and was credited with saving the Luhya tribe. It was also said to be used when building a ceremonial house for male circumcision. *Spathodea campanulata* (also called 'nandi flame' or 'African tulip tree') was believed to repel mosquitoes by smell and to prevent lightning striking to the house when it flowered. One farmer also said that *Cypressus* was used as a Christmas tree. No farmer planted crops for cultural services. However, 18 out of 20 farmers had plants for decoration purposes only (two crop-livestock farms had no ornamentals).

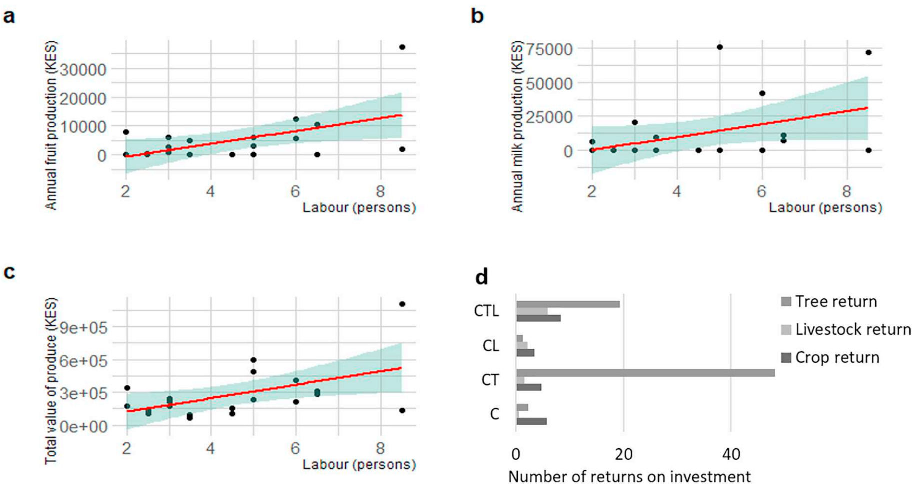

Fig. 4. Significant positive relations between family labour and annual a) value of fruit (P = .01) and b) milk (P = .04) production (Kenya Shillings - KES) per farm, and c) total annual value of produce (crop, animal, tree) expressed per farm area (ha) (P = .04). The line indicates the linear trend from the linear model and the shaded area shows the confidence interval. In d), the annual return on investment (ROI = (Revenue-Investments)/Investments) for the three farm components trees, livestock and crops is illustrated for the high or low tree and livestock density farms (no statistics done). Crop-tree-livestock farms (CTL) were selected to have high tree and livestock density; crop-tree farms (CT) to have high tree and low livestock density; crop-livestock farms (CL) to have low tree and high livestock density; and crop farms (C) to have low tree and livestock density.

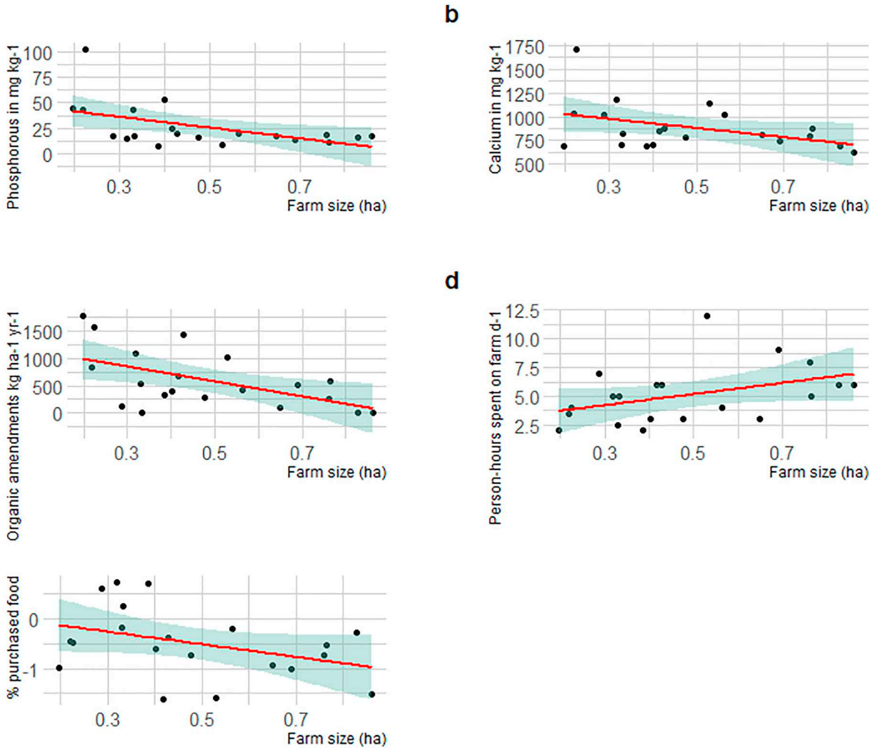

Fig. 5. Significant negative relations with farm size were found for a) soil phosphorous (mg P kg^{-1} soil; Mehlich) (P = .008), b) soil calcium (mg Ca kg^{-1} soil; Mehlich) (P = .04), c) application of organic soil amendments, i.e., manure and compost (kg ha^{-1} yr^{-1}) (P = .02) and e) percentage of purchased food of total food consumed (in monetary terms) (P = .04). There was a positive relation between d) person-hours spent on the farm per day and the farm size (P = .008). The line indicates the linear trend from the linear model and the shaded area shows the confidence interval.

There was no difference in the share of livestock species used for cultural services (like pets or for status) between high and low tree and livestock density farms. For livestock the share ranged between 1–3.9% compared to 7–54% for tree species. Livestock were generally kept for productive reasons (to get milk, eggs, meat, manure, or offspring) or in order to provide a certain service (plough, security, vermin control). Indirectly, both livestock and trees were also assets that could be sold if needed and thereby acted as savings. Doves, cats and dogs were kept as pets by a few farmers and one farmer said another benefit of having a dog was to feel proud. However, the doves were also eaten and kept in order to warn about the presence of snakes. Dogs were mainly kept for security, while cats were kept in order to keep rats and snakes away. Family labour or farm size had no associations with the cultural ES indicators.

3.5. Farm priorities

3.5.1. Nutrient management

The amount of organic (manure or compost) and inorganic fertilizer applied to crops varied between high and low tree and livestock density, with average rates of 505–689 kg ha^{-1} for organic materials and 91–147 kg ha^{-1} for inorganic (Table 3). However, there were no significant associations with either tree or livestock density, or family labour. A negative association was instead found between farm size and added organic amendments per ha (P = .02, Fig. 5c). Livestock density had, as expected, a positive association (P = .001) with the proportion of maize residues that were used for fodder. High livestock density farms utilized on average 38% of maize residues for fodder compared to just 3% on low livestock density farms. However, there were no significant relationships between tree or livestock density and the proportion of maize residues returned to fields, which was on average below 15% for all except C farms (average 40%) (Table 3).

3.5.2. On and off-farm resources

The proportions of on and off-farm revenue and the time spent on farm work differed among the farm types and both of them were related to tree density (Fig. 3). Farmers with high tree density spent more (P = .05, Table 3) person-hours per day (6.2 h) working on their farms compared with farmers with low tree densities (4.0 h). The highest workload was on CTL farms with 7.3 h per day of work on average (Supplementary Fig. 1a). Proportions of off-farm revenue were on average 12 and 41% for high and low tree density farms respectively (Table 3). The same number for C farms was on average 57%. The proportion of off-farm revenue of total revenues and value of produce showed a negative association (P = .02, Supplementary Fig. 1b) to tree density, but not to any other factor. Total off-farm revenue ranged, on

Table 3
Results of selected farm priority key variables (mean and 95% confidence intervals (CI)) for the study farms with high or low tree and livestock density ($n = 20$).

No	Key variables and units (farm average unless stated)	Low tree density	High tree density	Low livestock density	High livestock density	Significant results
		Mean (95% CI)[a]	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)	
	Nutrient management					
1	Annual organic amendments manure/compost (kg ha^{-1})	505 (180–829)	689 (365–1013)	547 (218–877)	646 (317–976)	F P = .02 −
2	Annual inorganic amendments in maize/bean fields (kg ha^{-1})	101 (36–167)	136 (71–201)	147 (80–213)	91 (24–157)	
3	% maize residues returned to field (left or composted)	21 (10–39)	12 (5–23)	23 (11–42)	10 (5–22)	
4	% maize residues used as fodder	12 (4–30)	12 (4–28)	3 (1–9)	38 (16–65)	L P = .001 +
	On and off-farm resources					
5	Land per capita (ha person^{-1})	0.10 (0.06–0.13)	0.11 (0.07–0.15)	0.10 (0.06–0.14)	0.10 (0.07–0.14)	F P = .0003 + B P = .001 −
6	Average person-hours spent on farm work day^{-1}	4.0 (2.7–5.4)	6.2 (4.8–7.5)	4.7 (3.3–6.1)	5.5 (4.1–6.9)	F P = .04 + T P = .05 +
7	Annual total off-farm revenue farm^{-1} (1000 KES)	86 (50–122)	49 (13–85)	85 (48–122)	50 (13–87)	
8	% off-farm revenues of all revenue and value of produce[b]	41 (21–65)	12 (5–26)	24 (11–45)	23 (10–44)	T P = .02 −
	Food and consumption					
9	% purchased food of total food consumed	39 (30–47)	37 (29–46)	46 (37–55)	31 (23–39)	F P = .04 − L P = .02 −
10	% of revenues used to buy food	21 (15–29)	20 (14–27)	23 (17–31)	18 (13–25)	
11	Milk consumption farm^{-1} year^{-1} (1000 KES)	6 (3 − 12)	10 (5–21)	7 (3–16)	8 (4–16)	
12	Fruit consumption farm^{-1} year^{-1} (1000 KES)	4 (0–8)	6 (1 − 10)	4 (0–9)	6 (1–10)	B P = .02 +
	Species diversity					
13	No. of crop species farm^{-1} year^{-1}	9.8 (8.8–10.9)	11.5 (10.4–12.5)	10.6 (9.5–11.6)	10.7 (9.7–11.8)	B P = .02 + T P = .03 + T:L P = .03
14	No. of livestock species	3.1 (2.6–3.7)	2.7 (2.1–3.3)	2.4 (1.9–3.0)	3.4 (2.8–3.9)	B P = .01 + L P = .04 +
15	No. of tree species	9 (4–15)	28 (22 − 33)	17 (12 − 22)	20 (15–25)	B P = .02 + T P = .0004 +
16	No. of fruit species	1.1 (0–2.2)	2.6 (1.5–3.8)	2.1 (1.0–3.3)	1.6 (0.4–2.7)	T P = .05 +
17	Tree diversity Shannon index	1.47 (1.17–1.76)	1.97 (1.67–2.27)	1.79 (1.49–2.10)	1.64 (1.34–1.95)	T P = .02 +

Key variables measured in percentages were logit transformed (Eq. (3)). Significant results in the last column are based on associations (positive with + and negative with −) the factors of settlement (S), tree density (T), livestock density (L) and the interaction between tree and livestock density (T:L) as well as the co-variates of farm size (F) and family labour (B) in a linear model.
[a] In case confidence intervals included negative values, they were adjusted to 0.
[b] Gifts to the household was neither included in off-farm income nor in total income. However, gifts were included and shown in Fig. 6.

average, between 49,000 and 86,000 KES among low and high tree and livestock density farms, but no significant associations were found. Livestock density was not associated with any key variable for on and off-farm resources and tree density showed no relation to land per capita. Instead, as could be expected, a larger farm was connected to more land per capita (P = .0003) just like more family labour meant less land per capita (P = .001). A larger farm size also meant more time spent on farm work (P = .04). Family labour was not associated to any other variable than land per capita.

All farmers had different livelihood strategies (Fig. 6). Crop farms relied heavily on off-farm revenues (with more than 50% of revenues coming from off-farm), whereas CL farms had problems making ends meet without selling land and bricks (i.e., soil) to manage their expenditures (Fig. 6). The CT farms sold much of their crop harvest in order to buy the foods they preferred and these farms also received substantial money from relatives. The CTL farms mainly relied on revenues from trees, livestock, and when working as casual labour, and had the highest turnover rate in real numbers (smallest turnover rate per person) due to their large families (Table 1).

3.5.3. Food and consumption

Purchased food as a proportion of total food consumed (economic value) decreased both with larger farm size (Fig. 4e) and higher livestock density (Fig. 5f) (P = .04 respectively P = .02, Table 3), but was not affected by tree density or family labour. Close to half (45–48%) of all food was bought on CT and C farms, while the proportion was 31% on CL and CTL farms. The proportion of revenues used to buy food ranged between 18 and 23% and was not affected by any of the analyzed factors. The milk consumption ranged between a value of 6000 and 10,000 KES and fruits were 4000 to 6000 KES on average per year and farm. There were no significant associations with tree or livestock density, or farm size on average milk or fruit consumption per year and family. However, family labour had a positive relation to fruit consumption (P = .02, Fig. 7a).

3.5.4. Species diversity

The annual crop diversity was on average 9–12 crops per farm and year (Supplementary Fig. 1d). An interaction between tree and livestock density indicated that farms with high livestock density had similar crop diversity irrespectively of tree density, while for farms with low livestock density the tree density played a significant positive role for crop diversity (P = .03, Table 3). CT farms had a significantly higher average number of crop species compared to C farms (Supplementary Fig. 1d). More family labour was related to higher species diversity of crops (P = .02, Fig. 7b), livestock (P = .01, Fig. 7c) and trees (P = .02, Fig. 7d), but was not related to Shannons index (Eq. (2), Table 3). Tree density had a positive relationship with the number of tree species (P = .02), number of fruit types (P = .04) and Shannon's diversity index for trees (P = .02, Supplementary Fig. 1c, Table 3). The diversity of trees ranged between on average 9 species on low tree density farms to 28 species on high tree density farms. Tree density was not related to livestock diversity. Livestock density was similarly positively related to number of livestock species (P = .04), which was between 2 and 3 species on average per farm but was not linked to tree diversity. Farm size had no association with species diversity for crops, trees or livestock.

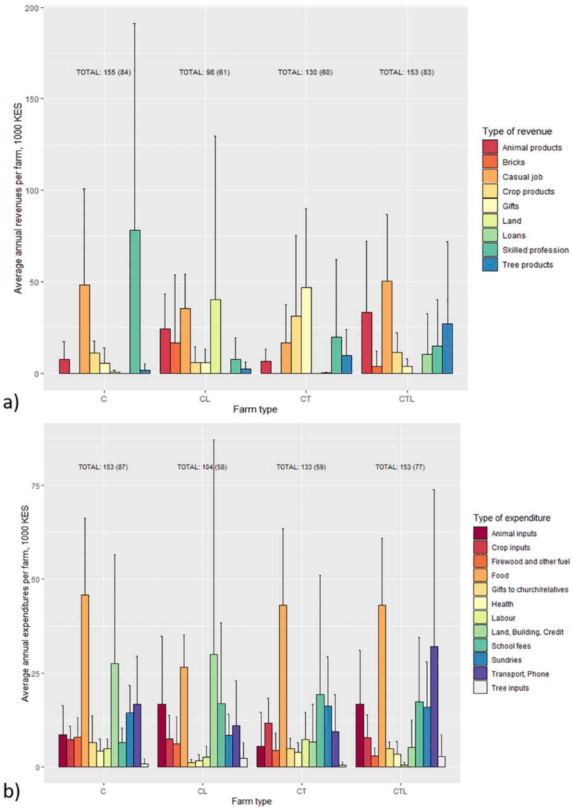

Fig. 6. Average mean values and standard deviation of annual a) sources of revenues and b) expenditures per farm in thousand Kenya Shillings (KES) for the high or low tree and livestock density farms and their combinations (Fig. 2; $n = 20$). Total annual revenue and expenditure per farm are given in numbers above the histogram with standard deviation in brackets. Crop-tree-livestock farms (CTL) were selected to have high tree and livestock density; crop-tree farms (CT) to have high tree and low livestock density; crop-livestock farms (CL) to have low tree and high livestock density; and crop farms (C) to have low tree and livestock density.

4. Discussion

4.1. Provisioning services

Crop production and total farm production were not affected by tree or livestock density. The fact that high tree density did not result in lower crop production (although trees and crops can compete for light, water, and nutrients) could be because crops can benefit from ecosystem services provided by trees, such as improved water infiltration or nutrient cycling (Kuyah et al., 2016; Rao et al., 1997). Otherwise it could be due to that only few trees were located within the maize and bean fields. The recorded maize yield was lower than reported by Nyaga et al. (2017) for larger farms in the same area. However, it was similar to those observed by Kiboi et al. (2017) in Kenya's Central Highlands in the same year and also within the mean of Kenyan average maize production 2009–2013 (1.5–2.0 t ha^{-1}) reported by Ministry of Agriculture, Livestock, and Fisheries in Kenya (in Sheahan et al. (2016)).

Production of tree and livestock products such as fruit, firewood, milk and eggs showed no statistically significant associations with tree or livestock density. This is probably due to a large variation within the farm types. However, higher tree density demanded more person-hours of work. At the same time, available family labour was the only factor that positively affected several provisioning ES indicators. Based on this, it would have been interesting to include more farms and of a larger range in size in the study. An alternative way to design the study could also have been to have tree and livestock density as continuous variables, which would have required different selection criteria for the farm selection, in order to see if effects for trees or livestock could come out more clearly.

Family labour had positive associations to fruit, milk and total farm production. With a future global challenge of increasing food production without expanding agricultural areas (Foley et al., 2011), this shows potential for improvements in intensification of production through more and effective use of labour (Dorward, 2013). Sustainable ways of mechanization should be addressed to attract a young generation of fulltime smallholder farmers to develop sustainable and profitable farm enterprises (Baudron et al., 2015). In addition, there was no relation between farm size and crop, tree or livestock provisioning services. Since tree and livestock products were measured per farm and not ha^{-1}, this suggests that tree and livestock productions do not necessarily need large land areas.

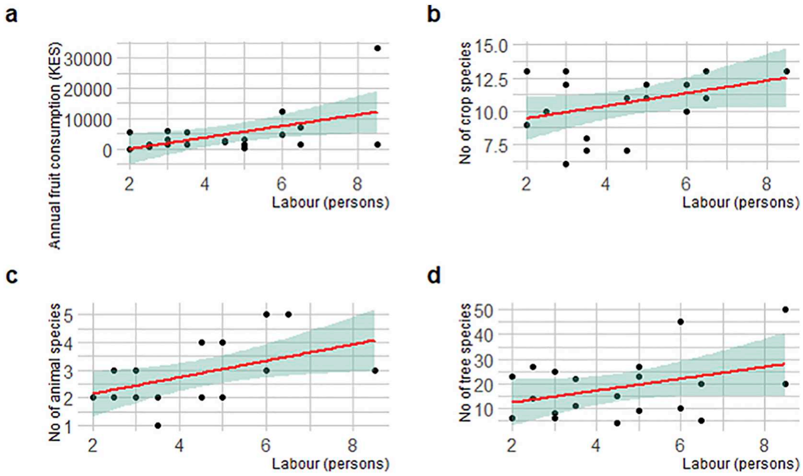

Fig. 7. Significant positive relations between family labour and a) annual fruit consumption ($P = .02$), b) number of crop ($P = .02$), c) livestock ($P = .01$) and d) tree ($P = .02$) species on the farm. The line indicates the linear trend from the linear model and the shaded area shows the confidence interval.

Return on investment was lowest for livestock products, probably due to extensive milk production and that farmers value livestock high as a security (Jerneck and Olsson, 2013). The high ROI for trees is related to the long rotation period of trees in some cases. The investments are high when planting trees but little investment is required in later years and high revenue could be returned from harvesting small numbers of trees. The importance of a planned balance between planting and cutting is clear and was practiced on the majority of farms. Farms with a combination of high tree and livestock density gave on average the highest ROI for both crops and livestock, while CL farms gave the lowest crop and tree ROIs. Potentially this may indicate that trees have positive associations to other production, even if not significant in a small sample of farms like this.

The household economy presented here included only revenues, expenditures, and values of products that were used, sold or bought during one particular year (Fig. 6). The value of possession of land, livestock, trees, other assets, or savings during the study period were not considered. However, these assets can provide important insurance (Kearney et al., 2017). Overall, the average annual revenue of the study farms ranged between 98,000 and 155,000 KES a year or 268–425 KES a day, which equals to 2.6–4.2 USD a day, and can be compared with the extreme poverty line of 1.90 USD a day (Worldbank, 2019). The livestock component was associated with relatively high expenditure compared with crops or trees, but a milking cow is highly attractive, resulting in potential daily revenues and reduced food expenditure (as found in this study). The same reasoning could potentially apply to the lower expenses for building materials, land, and credits for high tree density farms, as wood can be assumed to come from within the farm. Crop-livestock farms had the lowest total revenue and lowest revenue from crops (Fig. 6), indicating that they had more difficulty making ends meet. The ROI for livestock products however seemed to increase with tree density (Fig. 4). Crop-livestock-tree farms were more self-sufficient than others with on average higher production and revenue from the farm.

Decreasing farm size leads to households becoming gradually more dependent on off-farm revenue sources (Mutoko et al., 2014). The role of farm size has been highlighted earlier (Fan and Chan-Kang, 2005), but the threshold farm size to sustain a household has yet to be determined. However, the farm size in this study (0.2–0.8 ha) seems to be near the threshold, since C farmers seemed to use their farm more as an additional source of food and had a relatively high proportion (57%) of off-farm revenue (Table 3).

4.2. Supporting and regulating services

Poor management of both cattle and the manure itself is common in these areas and leads to low amounts of nutrients returned to the soil (Castellanos-Navarrete et al., 2015). But even when storage and application losses are considered, manure has been found to be the largest contributor of major crop nutrients to Kenyan soils, and crop residues were found to be the cheapest (Castellanos-Navarrete et al., 2015). Long-term application of manure, compost, and/or crop residues can be expected to improve infiltration capacity (Ouattara et al., 2007) and increase carbon sequestration (indicated by the SOC content) (Hemmat et al., 2010). However, no significant associations between tree or livestock density and water infiltration or SOC were found. Instead a larger farm size meant lower concentrations of available soil P and Ca per unit area and lower application rate of organic amendments. Partly this could be explained by that TLU was not correlated to farm size, i.e., the manure was spread over a larger area. In further research, it would be interesting to include farms with even higher livestock density to get more input to the supporting and regulating ES discussion. That would likely mean that larger farms would have to be included, which also could have made it easier to find and understand the contributions of tree and livestock density for ES and farm priorities better.

4.3. Cultural services

Recreation and aesthetic enjoyment are the most commonly measured cultural services (Egoh et al., 2012), and in this study they were represented by on-farm indicators. It was found that crops were only planted for provisioning purposes even if all except two CL farms (90%) had additional ornamental plants. This is a clear sign that beauty is highly valued by smallholders as has been shown earlier (Franzel and Scherr, 2002). Unlike in other parts of the world (Roy, 1955), few livestock (partly doves, dogs and cats) had any cultural values. But instead, trees carried several important cultural services (e.g., shade for recreation in the homestead and beauty for aesthetic values) that were prioritized even on farms with low tree density. Shade is very important in agricultural landscapes where temperatures are high (Chambers and Longhurst, 1986) and can also promote social interaction in smallholder communities (Quandt et al., 2018). Shade was also found to be the third most common use of trees in Western Kenya by Reppin et al. (2019). Trees are however often planted for multiple purposes (Mekoya et al., 2008) and several examples of traditional beliefs were found here, just like in an earlier study (Diawuo and Issifu, 2015). These results are particularly interesting since primary data on cultural services commonly are retrieved from natural parks set aside for recreation and tourism (Egoh et al., 2012), while cultural services present within the agricultural landscape are rarely accounted for (Kuyah et al., 2016).

4.4. Farm priorities

4.4.1. Nutrient management

Livestock had a positive association with the proportion of maize residues fed to livestock, but no association with other organic (manure and compost) or inorganic amendments (fertilisers). Another Kenyan study found that around 50% of crop residues were returned to fields, while the other 50% were used as fodder or fuel for cooking (Berazneva et al., 2018). In this study an even smaller proportion of residues (< 15% on all except C farms) was returned. Crop residues are the cheapest nutrients to return to the soil, but smallholders often feed them to livestock or burn them (Castellanos-Navarrete et al., 2015; Tittonell et al., 2015). A portion of the nutrients contained in the residues fed to livestock will be returned to the soil if the manure is used. With higher livestock density one could expect the applications of manure to be larger compared with low livestock density. However, in this study no associations between livestock and nutrient dynamics were found, using the amount of manure or soil nutrient concentrations as indicators. The results may reflect the small farm sizes. Farms smaller than one hectare have difficulties in maintaining soil fertility and productivity, since their ability to accumulate cash for productive investments is minimal (Stephens et al., 2012).

4.4.2. On and off-farm resources

Farms with high tree density had higher proportion of on-farm revenue and lower proportions of off-farm revenue. The results could indicate a higher market orientation and/or a higher self-sufficiency orientation. The higher market orientation is reflected in higher revenues from tree, crop and livestock products (Fig. 6), and higher self-sufficiency through less fuel expenditures and lower proportions of off-farm revenues. High tree density indicated more hours of work on-farm, perhaps an indication of a more long-term commitment to the farm. The extra work hours needed on high tree density farms may potentially give them less time to work off-farm. In other studies, trees (especially in woodlots) are normally associated with reduced labour demand (Dewees, 1991). Most trees need only seasonal or annual attention compared to daily or weekly attention for livestock and crops, and trees save labour through e.g., easy access to fuelwood. However, in cases of agroforestry with e.g., high numbers of trees in hedgerows, the labour requirement is higher (Hoekstra, 1987). Earlier research has indicated that production can be increased with more intensive farm management, but it may not pay off unless the labour is from within the family (Mutoko et al., 2014). Family labour and production were found to be positively associated also in this study. Using more family labour to produce mainly for the market rather than for consumption has been found to improve the production efficiency on smallholder farms (Mutoko et al., 2014), while hiring labour is not economically efficient according to Dewees (1991). However, there is a need for more research on the relationships between labour demand and crop production for certain management practices, since they have been found to be closely related (Dahlin and Rusinamhodzi, 2019). The lack of associations to livestock density could indicate that a larger variation in livestock density is needed to detect clear differences among these variables.

Available land per capita was positively associated to farm size and negatively associated to family labour which is quite logical but also means that smaller farms with larger potential family labour force has to be more intensive or rely more on off-farm revenue. All 20 study farms had relatively large parts of their revenues from off-farm (on average 12–41%, Table 3) compared to a study of smallholders in Ethiopia where the average was 9% (Kebede et al., 2019). Crop farms had the largest proportions of off-farm revenues (Fig. 3), possibly indicating a direction of exiting farming for those households (Appel and Balmann, 2019).

4.4.3. Food and consumption

The proportion of revenues used for purchasing food was similar between farms in this study (18–23%) and as compared to smallholders with similar land per capita in Ethiopia (24%) (Kebede et al., 2019). However, increased livestock density and farm size both lead to smaller proportions of purchased food of total food consumed. For example, milk is a relatively expensive food item that is commonly used for tea every day (Hansen et al., 2011) and may therefore partly explain the results. The larger farm size gave larger land per capita, which should naturally lead to a lesser need for purchased food, especially since labour was not associated with the proportion of purchased food. Lower proportions of purchased food could be a sign of higher self-sufficiency.

Several studies have found a positive relationship between tree cover and dietary diversity (Ickowitz et al., 2014; Sibhatu et al., 2015), while having livestock correlates with higher milk consumption (Nicholson et al., 2004). However, Sibhatu et al. (2015) found that off-farm revenue also had positive associations with dietary diversity, but that differences were less clear in e.g., Kenya, where smallholders had relatively high overall diversity. The relatively high diversity in the study area could explain the lack of significant differences between high and low tree density in terms of milk and fruit consumption. The higher fruit consumption found when available family labour was high, can either simply be due to more people eating fruit or that it takes more labour to make the most of the fruit products at a certain time.

4.4.4. Crop, tree and livestock species diversity

Tree density and family labour were positively associated with several variables related to on farm diversity of crops, trees and livestock, even if crop diversity generally was high on the majority of farms (9–12 crops per farm). Diversifying farming systems is recommended in order to secure sustainable and robust future global food production (Kahane et al., 2013). Our results showed that farms with higher tree and livestock density also had larger crop species diversity. This was probably related to that farmers with high tree density spent more time on farm-work and therefore could attend to a larger number of crop species. In other words, high tree density was perhaps an indication of farms that had chosen a diversification trajectory, investing both in market orientation and self-sufficiency. Crop diversification on smallholder farms has further been found to increase farm revenues (Nguyen, 2017), that can be connected to the higher proportion of on-farm revenue for high tree density farms in this study.

The Shannon index for tree diversity ranged between 1.47 and 1.97 among high and low tree density the farms included this study (Table 3), which is slightly lower than results reported by Nyaga et al. (2015) on farms of a larger size range in the same settlements (1.83–2.31) but similar to the farm average found by Reppin et al. (2019) in Western Kenya (1.65).

4.5. Farm trajectories

Based on the results of this study, there seem to be two directions or trajectories for smallholders with 0.2–0.8 ha of land: towards a higher diversity of crops, trees and livestock, or towards a simpler farming system with just a few crops. The former is more labour demanding, but also potentially more productive and resilient (Cabell and Oelofse, 2012) and has been identified by Kebede et al. (2019) as a diversification trajectory, which is common with shrinking farm sizes. The simpler farming system is relatively sensitive to disturbances, but makes it easier for the owner to seek a higher proportion of off-farm revenue and thereby relying less on the farm performance, which is a way of getting a resilient revenue but not a resilient farm. In one sense this is a specialization trajectory, where farmers focus on a limited number of crops, but it is also a kind of exiting direction since off-farm revenue will slowly overtake the on-farm revenue or value, which was already the case on some of the studied farms. The more diverse farms seemed to be both more market-oriented as well as more self-sufficient in their production than the less diverse farms.

5. Conclusions

This study confirmed roles of trees and livestock for ES and farm priorities, although they in some cases appeared less important than family labour and farm size. Tree or livestock density alone showed no clear associations with provisioning, supporting or regulating ES. Cultural services like recreation and aesthetics were provided mainly by trees and were of high priority on the study farms.

High tree density was associated with higher crop, fruit and tree species diversity. It also resulted in a higher workload and meant higher proportions of on-farm revenue. Trees are more long-term products and investing in trees could be related to longer-term commitment to the farming system. High livestock density showed a reduced proportion of purchased food, probably meaning that milk for consumption was the main benefit from high livestock density.

The overall finding was that both tree and livestock density, among these 20 farms, seemed to have inferior associations to ES and farm priorities compared to family labour and farm size. The available family labour positively influenced both farm outcome (provisioning services) and risk spreading (crop, tree and livestock species diversity). The use of organic amendments (manure, compost) and mineral fertilisers was overall low, and the application rate per unit area seemed higher on farms with less land which was reflected in higher soil P and Ca concentrations. The nutrient supply and soil fertility need to be boosted on smallholder farms, e.g. through better integration of crop and livestock production, re-use of crop residues and inclusion of nitrogen fixing plants, e.g. grain legumes and leguminous fodder shrubs. Nutrient cycling and the use of plant nutrients and organic matter needs to be improved and more efficient to sustainably enhance productivity in smallholder agriculture.

Crop farms relied significantly more on off-farm revenue compared to the other farm types, and seemed to be in a trajectory of exiting farming. Farms of high tree density had signs of both a higher level of market orientation and self-sufficiency, but they also had higher labour requirements. The challenge of (too) small farm sizes and reducing farm sizes need to be targeted seriously in research and development efforts aiming at sustainable intensification and diversification of smallholder farming and market opportunities. Also the issue of labour requirement and pathways for mechanization must be addressed to attract a new generation farmers to develop sustainable and profitable farm enterprises providing ES to the farm and the surrounding landscape.

Declaration of competing interest

No potential conflict of interest is reported by the authors. All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments, or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2020.102815.

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This thesis examined how Kenyan smallholders manage their farming systems to adapt to rainfall variability and improve productivity, while also maintaining sustainable delivery of multiple ecosystem services. The results indicate that smallholders were aware of suitable sustainable management practices to use, but uptake was limited by lack of capital, knowledge, land and labour, especially for low-educated women. Higher tree density increased the workload, but also the proportion of on-farm income, and trees were important for cultural ecosystem services.

Ylva Nyberg received her postgraduate education at the Department of Crop Production Ecology, Swedish University of Agricultural Sciences. Her Master of Science in Agriculture was obtained at the same university.

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